USE OF A MECHANICAL MODEL TO SHOW THE BENEFITS OF MODERN ANATOMICAL FEATURES OF HOMO SAPIENS FOR HEAD STABILIZATION DURING RUNNING

by

Joseph D. Alston

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STATEMENT OF THESIS APPROVAL

The thesis of **Joseph D. Alston**

has been approved by the following supervisory committee members:

Sanford Meek	, Chair	**May 13, 2010** Date Approved
Stacy Bamberg	, Member	**May 13, 2010** Date Approved
Dennis Bramble	, Member	**Nov 10, 2010** Date Approved

and by **Tim Ameel** , Chair of

the Department of **Mechanical Engineering**

and by Charles A. Wight, Dean of The Graduate School.

ABSTRACT

Stabilization of the head is critical for running. *Homo sapiens* possess several anatomical features that are useful for head stabilization. In order to test the functional value of some of these features, namely the location of the center of mass and the muscular connection between the skull and shoulder girdle, mechanical models are created. These mechanical models are representative of *Homo sapiens* and their ancestors. These models are subject to the kinematics and dynamics of a complete running gait cycle. The results show that the location of the center of mass for the *Homo sapiens* is superior to that of its ancestors for the purposes of head stabilization. Furthermore, the results show that the muscular connection between the skull and the shoulder girdle of *Homo sapiens* permit the counter rotation of the shoulders to reduce the energy needed to stabilize the head during running.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

As a point of uniqueness, *Homo sapiens* (HS) are the only living hominid to transverse in a bipedal fashion. HS transverse by placing one foot in front of the other, maintaining one foot on the ground at all times, i.e., walking. Evermore impressive is HS transverse by jumping from one foot to the other, i.e., they run. Not only can they just simply run, HS can run for hours on end. Critical to running is stabilization of the head for the purpose of maintaining a functioning visual system. The visual system of a HS begins to lose the ability to track moving objects when the objects are moving above 100 deg/sec with respect to the eyes (Meyer, Lasker and Robinson 1985).

To understand the phenomenon of bipedal running, scientists have identified several features that aid in bipedal locomotion. One of these features is the structure of the head and shoulders of HS. While these features can be identified, the full implications of the development of these features are not always known. Some of the questions to be asked about the head and shoulders are as follows: What is the significance of the change in the occipital-atlanto joint of the genus *Homo* through evolution? What is the significance of the change of the center of mass (COM) of the genus home through evolution? What is the importance of the shoulder movement of the shoulders? The purpose of this paper is to examine these questions.

1.2 Thesis

The theory examined in this paper is that part of the evolution of the genus *Homo* includes features that enable it to effectively stabilize the head during running. The effectiveness of head stabilization means that holding the head steady requires minimal energy through a complete running cycle. The anatomical features that are examined in this paper are the COM of the head, the movement of the shoulders, and the muscular connections between the head and shoulders.

1.3 Method

In order to prove that the head and neck complex in humans has evolved to enable better head stabilization, the kinematics and dynamics of humans and their ancestors need to be analyzed. Ideally, the method to analyze these anatomical features in the context of effective head stabilization would be to have a multiple species of the genus *Homo* run on a treadmill and measure the muscle activity of the neck and shoulder muscles and determine the forces applied. However, such an experiment is impossible because HS are the only living hominids that actually run. Therefore, an alternative is to invert the problem; create a mechanical model and determine the forces needed for the model to move in a prescribed manner. The analysis shows the forces and energy needed to hold the head steady while the rest of the body follows a motion that is representative of HS running. The parameters of the head are then modified to represent other hominids. The other hominids chosen are *Homo erectus* (HE) and a gorilla. The three basic cases, HS, HE and a gorilla, are chosen to provide a comparison between modern, ancestral and intermediate anatomies. The comparison of the forces needed to hold the head steady shows which case requires the least amount of energy. The case that does require the least amount of energy is the most effective at stabilizing the head during running.

CHAPTER 2

BACKGROUND

2.1 Biomechanics of human running

Many aspects of running are examined; kinematics, ground reaction forces (GRF), shoes, injuries, gender, etc. Along with these aspects, the efficiency of human running is also studied. Comparatively, humans do well as endurance runners. Many factors allow humans to be good endurance runners. These factors include, long legs, the shape of the feet, decoupled head from the shoulders, long Achilles tendon, more balanced head, etc. In order to make the scope of this study manageable, the anatomical factors that affect human running need to be limited. Thus, the factors examined in this study are the location of the COM of the head and muscle connections between the head and shoulders. These features did not start to develop to promote endurance running until *Homo habilis* (Bramble and Lieberman 2004).

From an evolutionary perspective, one the factors for endurance running that has been studied is the placement of the head COM. Given the nature of the fossil record, this factor is one that can be relatively easy to compare. Over the course of the evolution of HS and their ancestors, the posture of the body has become more upright. Part of this change in posture has resulted from change in the shape of the head. As the head has changed shape, the COM has moved posteriorly, resulting in a position more nearly above the occipital condyles. This move in the center of mass creates a more balanced head.

To compare this feature of HS with that of its ancestors, the location of the COM is scaled according to the horizontal distance from the ear to the bottom of the eye socket along the Frankfurt Horizontal (FH), see Figure 2.1 (D. Bramble 2010). By plotting the COM for HS and its relatives, a trend is created that describes how HS have evolved, see Figure 2.2 (D. Bramble 2010).

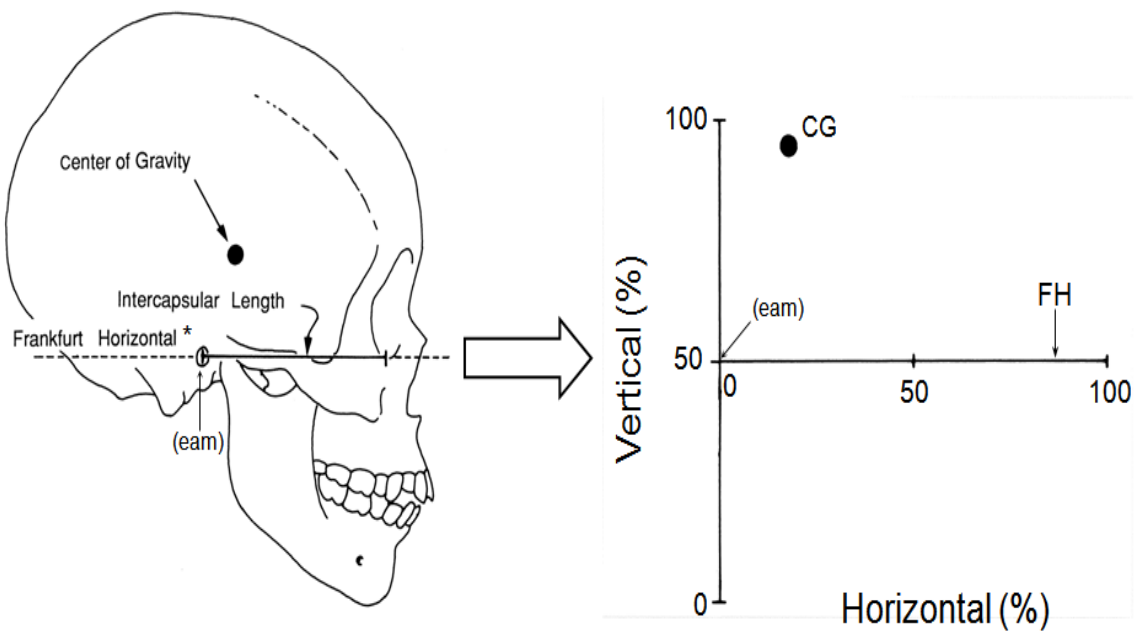

Figure 2.1: Definition of scaling factor, courtesy of Dennis Bramble (2010)

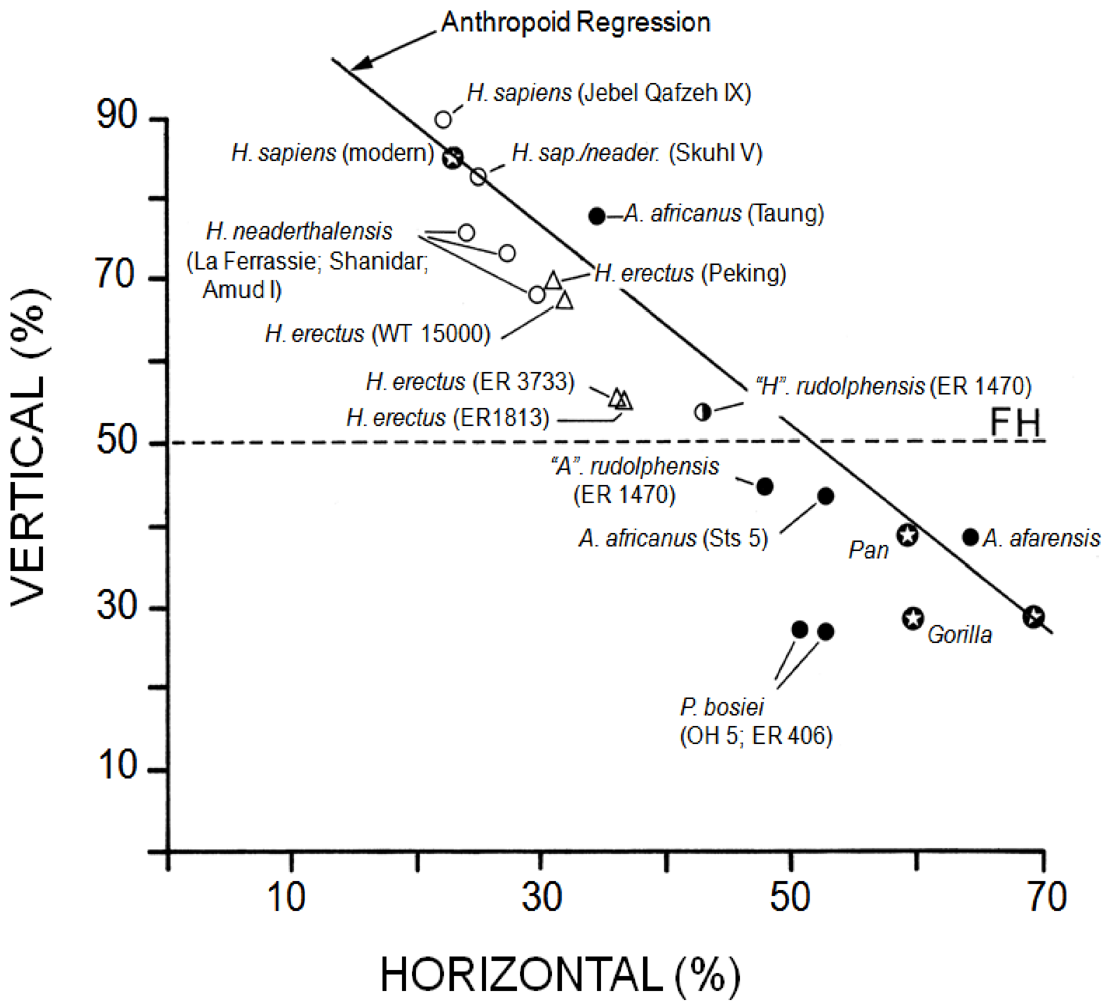

Figure 2.2: Evolutionary trend of skulls of the genus *Homo* and relatives, courtesy of Dennis Bramble (2010)

CHAPTER 3

SETUP

3.1 Introduction

To analyze the head, neck and shoulder complex of HS, or its relatives, a mechanical model for each system is created. These mechanical models, by their very nature, consist of a series of segments linked together with joints in a chain like fashion. Each segment is representative of a portion of a body with appropriate lengths, masses and inertial parameters. The connections between the segments are also appropriately representative of their respective anatomical joints, e.g., a ball joint to represent the glenohumeral joint, or a simple hinge joint to represent the knee. For the mechanical models to properly represent their respective anatomical test cases, actuators are added. These actuators represent the muscles of the test cases. Once created, the models are subjected to the kinematics and dynamics of running. In other words, the movement of each joint represents the movement of running. The model is also subjected to the GRF associated with running. With all of the geometries, masses, motions, and external forces, the individual responses of each joint or actuator is calculated.

3.2 Evolutionary assumptions

It is desirable to use simplifications and assumptions. The reason for using simplifications and assumptions is because this study is an analysis of biological systems. These systems are often very complex, difficult to measure, and difficult to analyze. Furthermore, the nature of the analysis is time dependant, which can comprise an amount of data that can be unwieldy. This study is a comparison between HS and its ancestors. Furthermore, some of the data required for the analysis are difficult, if not impossible, to obtain from fossils. The difficult to obtain data are tendon lengths, inertial parameters, motion data, GRF etc. This being the case, the assumption is made that the ancestral models will be sufficiently represented by modified modern HS models. These modified models will replicate the ancestors by having the center of masses of the skulls be adjusted to reflect what they would have been in life. Furthermore, the kinematic data and the external forces for HS will be applied to the ancestral models. Creating and analyzing the ancestral models in this fashion permits the effects of head and shoulder connectivity as well as head COM placement to be isolated and analyzed.

3.3 Chain-link dynamics

One of the basic means of analyzing a series of segments serially linked together in a chain is to use Newton-Euler equations in a serial fashion. Newton's equation, equation 3.2, is simply the derivative of the basic linear momentum equation, equation 3.1, where m_i is mass, p_i is linear momentum, $\dot{r}_{0i}$ is linear velocity, f_i is force, and $\ddot{r}_{0i}$ is linear acceleration.

$$p_i = m_i \dot{r}_{0i} \tag{3.1}$$

$$f_i = m_i \ddot{r}_{0i} \tag{3.2}$$

The analysis of a chain is performed by starting at an origin segment, determining the forces and moments of that segment, moving to the next segment, analyzing the forces and moments, moving to the next segment, and repeating the procedure until each segment has been analyzed. The formation of each segment requires an origin with its own coordinate system. In each segment's coordinate system, a center of mass and joint locations are established. Furthermore, each segment requires inertial parameters for the moments to be properly examined. Once all the information for the individual segments is acquired, the entire system can be examined (Hollerbach 2009).

3.4 Limitations

Some of the limitations of chain-link dynamics rest with how the segments are connected to each other. Generally the segments are connected with joints that are allowed to move in purely translational or rotational fashions. Although, some studies examine more complicated joints comprised of a combination of translational and rotational components (Arnold, et al. 2009). While these more complicated joints are available, their effect upon the results is dependent upon the ability to characterize the joints, and the cumulative errors associated with the other aspects of the model. If the joint cannot be sufficiently characterized, the joint could simply cause increased error in the results. Also, if the cumulative errors associated with the other aspects of the model outweigh the benefits of using the more complex joint, there is no point in using the joint.

Because the results of the analysis are intended to be of a comparative nature, joints comprised of simple rotational axes are judged to be sufficient.

3.5 Coordinate systems and joints

Each segment of the model requires its own coordinate system. The purpose of the individual coordinate systems is for the measurements of each segment to be referenced to a common point in their respective segment. For consistency, the coordinates systems that are used follow the systems presented by Wu, et al. in 2002 and 2005.

3.6 Anatomical data

As this analysis is a comparison between species, it is desirable to make a comparison between the 50th percentiles of each species. In order to do so, a large amount of data for each species would be necessary to create the statistical average. These data do not exist for HE or gorilla to the extent that they do for HS. Therefore, the 50th percentile data for *Homo sapiens* will be used. The statistical data for body measurement have been primarily collected through military measurements. The 50th percentile man is represented in Figure 3.1 (Tilley 2002). In addition to segment lengths and masses, three-dimensional (3D) inertial parameters for each of the segments are needed. The parameters used were generated by Dumas, Cheze and Verriest (see Table 3.1). Dumas derived parameters and equations that take body lengths and mass and generate COM and inertial parameters (Dumas, Cheze and Verriest 2007). The equation that Dumas created to determine the inertial parameters is as follows:

$$I_{ij} = m * \left(r_{ij} * L\right)^2 \tag{3.3}$$

where I_{ij} is the inertial parameter; m is the mass; r_{ij} is the radius of gyration; L is the segment length.

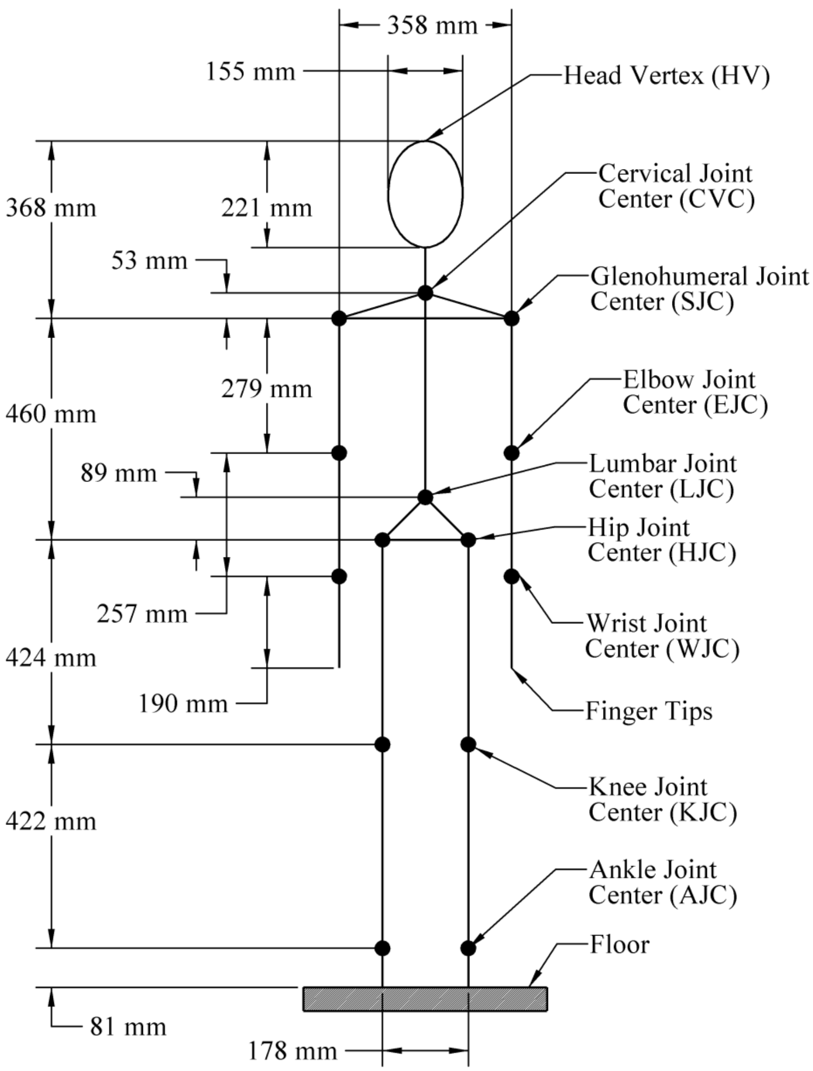

Figure 3.1: 50% percentile man adapted from Tilley (2002)

Table 3.1: Scaling factors for the Mass of Body Segment and inertial parameters, adapted from Dumas, Cheze and Verriest (2007).

Segment	Length definition	Mass scaling factor	Scaling factors for tensor of inertia					
			r_xx (%)	r_yy (%)	r_zz (%)	r_xy (%)	r_xz (%)	r_yz (%)
Head & neck	CJC to HV	6.7	31	25	33	9(i)	2(i)	3
Torso	CJC to LJC	33.3	27	25	28	18	2	4(I)
Arm	SJC to EJC	2.4	31	14	32	6	5	2
Forearm	EJC to WJC	1.7	28	11	27	3	2	8(i)
Hand	WJC to midpoint between MH_2 and MH_5	0.6	61	28	56	22	15	20(i)
Pelvis	LJC to projection of HJC in segital plane	14.2	101	106	95	25(i)	12(i)	8(i)
Thigh	HJC to KJC	12.3	29	15	30	7	2(i)	7(i)
Leg	KJC to AJC	4.8	28	10	28	4(i)	2(i)	5
Foot	AJC to midpoint between MH_I and MH_V	1.2	17	37	36	13	8(i)	0

3.7 Geometry

In order to analyze body motions, the body must be segmented into individual parts. The basic idea of segmentation is to divide the body into individual parts that can be represented as rigid links. The difficulty of such a task lies in the fact the body is a continuous, non-homogeneous mass. Adding to the difficulty, depending upon the position of the limbs, there is no clear dividing line for the muscles, tendons, and other tissues. Some reasonable dividing lines are at joints or body landmarks. However, these points also have problems as joints are not always stationary and both bony landmarks and joints vary from individual to individual. These problems are especially apparent along the spine and shoulders. Despite the complexity of the human body, a number of simplifications will enable easier modeling because of the focus of the study (Zatsiorsky 2002).

3.7.1 Lower body

As the lower body is often the primary focus in running analysis, an established method of simplifying the data recorded is to either completely ignore the upper body, or replace it with a place holder. As this analysis is the opposite, the lower body can be replaced with a place holder. This simplification is feasible because of the natural segmentation of the human body at the pelvis. The pelvis is a natural segmentation point because while there are many muscles, tendons, ligaments and organs that attach to the pelvis, very few actually span across it (Gray 2003).

3.7.2 Pelvis

The pelvis is not required but is included and used as an origin. The origin of the model is used as a common reference point to link the model to the environment. This allows for the kinematics of the model and the GRF to be applied to the model. In order to incorporate the position and orientation of the shoulders, and connect the shoulders with the neck, the torso is required. The torso is the collection of the spine and rib cage of the body. However, as an origin, the pelvis offers several advantages over the trunk. These advantages are as follows:

1. There exists a vast body of literature covering running. Much of it deals with the lower body and will include the pelvis (Novacheck 1998).
2. The pelvis is the attachment point for the legs and offers a convenient segmentation point.

3. The pelvis itself has also been the focus of several research studies. As a result of being the focus, or part of the focus, of past research studies, there are large amounts of data available (Schache, Bennell, et al. 1999).

4. Another positive quality of the pelvis is the availability of easily accessible landmarks. Stereophotogrammetry, or a motion capture system, is often used to record the kinematics of a subject. In order to collect motion data of a person, reflective markers will be placed on the skin and the person will be recorded while in motion. The data recorded actually relate to how the skin moves over the bones. If the skin moves very little with respect to the bones, then the data will be respectively accurate. The pelvis has the anterior and posterior superior iliac spines and the center of the acetabulum as available land marks that work for a motion capture system (Cappozzo, et al. 1995).

3.7.3 Torso

The torso, or trunk, is often defined as the continuous mass from the pelvis to the 7th cervical vertebrae that includes the spine, rib cage, shoulder girdle, and all tissues contained therein. While the torso is a continuous mass with moveable joints throughout its length, the complexity of this portion of the body makes segmentation difficult. Several previous studies simply keep the torso as a single rigid body; e.g., de Leva (1996), Dumas, Cheze and Verriest (2007), Kingma, et al. (1996) and Zatsiorsky (2002). Furthermore, for the purposes of the present study, the torso is only needed to properly orient and place the shoulders and neck. Therefore, the simplified version of the trunk as a solid rigid mass will be sufficient.

3.7.4 Shoulders

In several published studies, the trunk includes the shoulders, e.g., de Leva (1996), Dumas, Cheze and Verriest (2007), Kigma, et al. (1996), Tilley (2002), Young, et al. (1983), and Zatsiorsky (1998). However, for this study, the motion of the shoulders is critical to the results. The shoulder is a complex of tissues and bones that offer great mobility. The shoulder complex straddles the rib cage and contains the sternum, thorax, torso, clavicle, scapula, and humerus. The complex is broken into two different sections, the shoulder girdle and the glenohumeral joint. The shoulder girdle consists of the sternum, thorax, torso, clavicle and scapula. The glenohumeral joint is the joint that connects the humerus to the scapula. These bones work together to increase the range of motion that is otherwise afforded the glenohumeral joint. The kinematics of the shoulder works as a series of ball joints proceeded by a translational joint, see Figure 3.2 (Lenarcic, Stanisic and Schearer 2002).

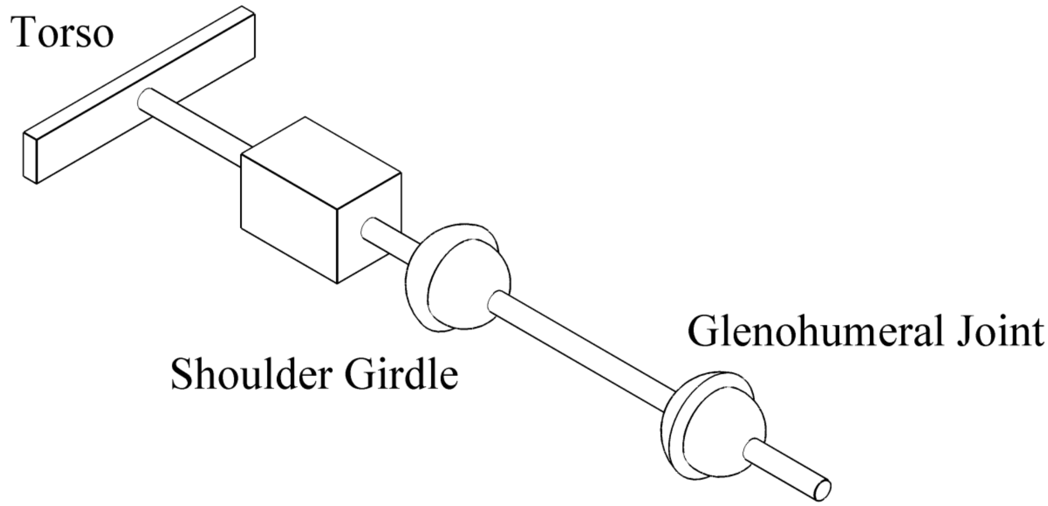

Figure 3.2: A serial humanoid should complex adapted from Lenarcic, Stanisic and Schearer (2002)

While knowing how the shoulder complex works to point the humerus is useful, for the study, the location of the shoulder joints with respect to time is required. Description of the 3D placement of the shoulder complex is known as the shoulder rhythm. A recent study of the shoulder rhythm produces a series of five linear regression equations. These equations define the orientation of the clavicle and scapula via the orientation of the humerus. The constants and coefficients for the linear equations are found in Table 3.2 (de Groot and Brand 2001).

Table 3.2: Linear regression parameters adapted from de Groot and Brand (2001).

	Constant (C)	Humerus elevation (H_y)	Humerus elevation plane (H_z)	Force direction (F)	Initial angle (X_0)
Clavicle protraction (C_y)	-4.983	0.120	0.242	0.008	0.851
Clavicle elevation (C_z)	3.917	0.046	0.123	0.350	0.493
Scapula protraction (S_y)	-1.203	0.140	0.049	0.363	0.901
Scapula lateral rotation (S_z)	3.095	-0.079	0.396	0.646	0.414
Scapula tilt (S_x)	0.659	-0.028	0.184	0.746	0.886

3.7.5 Arms

For a complete model, a representation of the arms is needed. While playing a supplementary role in running the arms are still needed. The arms are used for balance and to aid in counter rotation of the legs. Given the nature of the role of the arms, a sophisticated representation is not required. The arms will be represented by the segmentation of arm, forearm, and hand (Dumas, Cheze and Verriest 2007). The joints in the arm will simply be reduced to a simple rotation for the elbow. The joints in the wrist can be locked.

3.7.6 Neck

The musculoskeletal system in the head and neck region is fairly complex. Each of the eight cervical joints, from the bottom of C7 to the top of C1, has multiple degrees of freedom. This level of freedom allows the neck to move in a snake like fashion. The level of rotation for each joint is described in Figures 3.3 – 3.5. The possibility exists of the neck having the theoretical possibility of reaching any give position an infinite number ways. However, there are some groupings in how the neck moves. The occipital-atlanto-axial complex comprises the joints between the occipital condyles and the atlas, or C1, and between the atlas and the axis, or C2. These joints can move independently. The rest of the neck moves as a unit (Zatsiorsky 1998).

In order to simplify the neck complex, the following are considered: habitual movement and the range of typical head motion during running. During head nodding the first eight degrees are, as a rule, performed by the occipital-atlantal joint. The first 45 degrees of neck axial rotation are performed at the atlanto-axial joint (Zatsiorsky 1998). The motion for the neck is assumed to be the motion required to compensate for the motion of the pelvis and the torso and keep the head up-right. Thus, the range of motion for pitch and yaw during running is less than what the top two cervical joints typically allow, see Figures 3.3 – 3.5. Also, the tertiary rotation of the neck is roll. Given this information, the neck is modeled as a rigid body with yaw occurring at the C1-C2 joint, pitch occurring at the C1-skull joint, and roll is ignored.

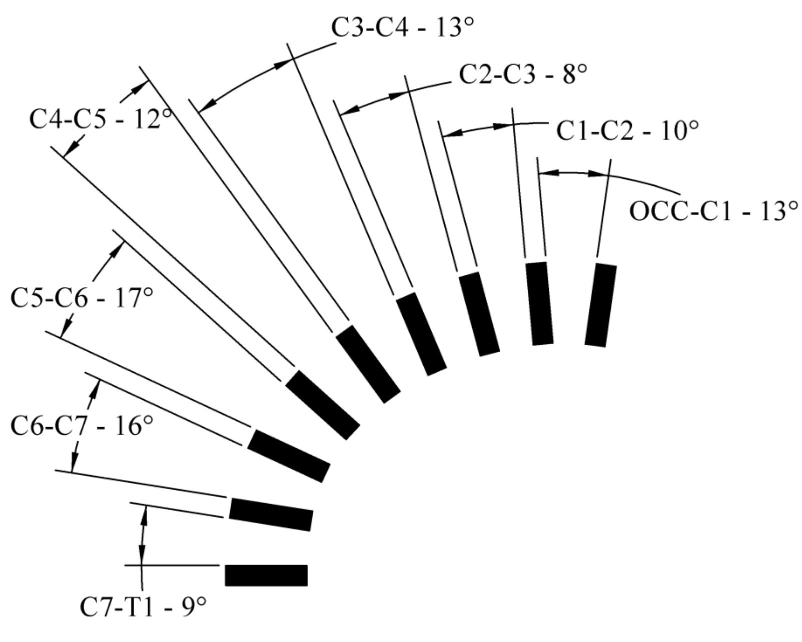

Figure 3.3: Flexion-extension range of motion in degrees of neck joints adapted from Zatsiorskey (1998)

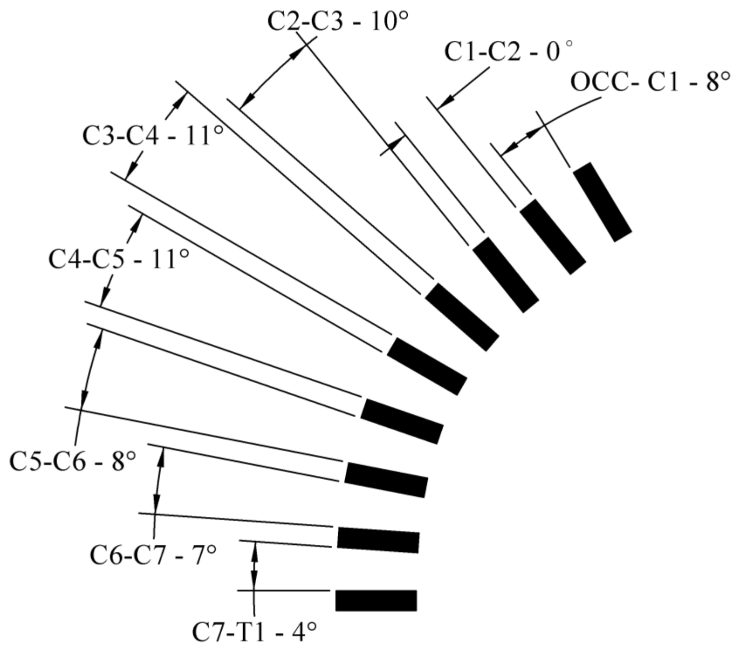

Figure 3.4: Lateral bending range of motion in degrees of neck joints based Zatsiorskey (1998)

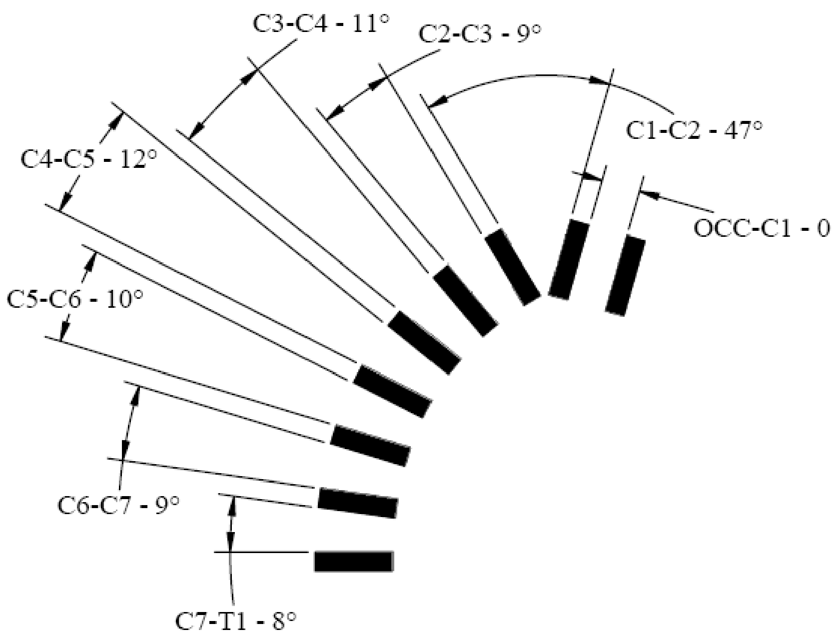

Figure 3.5: Axial rotation range of motion in degrees of neck joints adapted from Zatsiorskey (1998)

3.7.7 Head

As the head is part of the primary focus, a detailed representation is needed. Two characteristics are needed for proper representation; accurate placement of the center of mass and accurate muscle insertion points with respect to the C1- skull joint. Placement of the center of mass is achieved by accurate measurements of real skulls. Such data has been presented in numerous publications; e.g., de Leva (1996), Dumas, Cheze and Verriest (2007), Hatze (1977), Tilley (2002), and Yoganandan, et al. (2009). The data used in the present model is taken from Figure 2.2 which shows the location of the head COM with respect to the ear for HS and its relations. Figure 2.2 is very useful in showing the evolutionary trends of the COM for HS (D. Bramble 2010). The scaling factor for the models, taken from a graphical representation of a human skull generated with OpenSim, is .086 m, see Figure 3.6. In order to use that data in a dynamics model the location of the ear with respect to the atlanto-occipital joint is required. The distance from the atlanto-occipital joint to the ear for HS is taken from Figure 3.6. The same measurement is taken for HE from a picture of the side of a HE skull (Peking), see Figure 3.7 (D. Bramble 2010). Both measurements are shown in Table 3.3. Given the location of the ear and the scaling factor, the COM with respect to the HS and HE atlanto-occipital joints are given in Table 3.3 in the columns labeled COM and COM corrected, respectively. The location of the ear with respect to the atlanto-occipital joint for the gorilla was not readily available.

Table 3.3: COM location.

	Ear (m)		COM (m)		COM corrected (m)	
	horizontal	vertical	horizontal	vertical	horizontal	vertical
HS	0.0092	0.0200	0.0228	0.0533		
HE	0.0148	0.0113	0.0298	0.0398	0.0414	0.0281
gorilla COM			0.0549	0.0041		

Figure 3.6: Geometrical representation of a HS skull

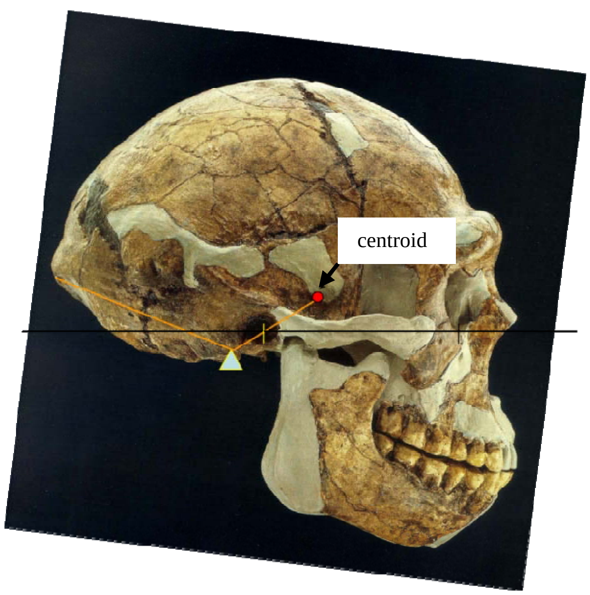

Figure 3.7: *Homo erectus* skull (Peking), courtesy of Dennis Bramble (2010)

3.8 Muscles

To make the model complete, actuators or muscles are needed. Essentially, muscles are strings attached to two different points that contract to cause motion. As this description entails, the muscles are modeled with lines attached to what are the insertion and origin points on the body. To accommodate the fact that muscles often connect to large areas, each major portion of a muscle is modeled by a string. As an example, the trapezius will have lines connecting each of the vertebrae to bones in the shoulders. While straight lines are nice, there are many muscles that wrap around joints when in motion, e.g., gluteus maximus, quads, triceps, etc. In order to model these muscles correctly, the muscles must be modeled as curved lines. However, due to the focus of the analysis, such measures are not necessary. All of the shoulder and neck muscles under consideration can be modeled as straight lines.

While the form of the muscle can be modeled as simple straight lines, the function of the muscle is more complicated. The standard for describing the force that a muscle can generate is Hill's model. This model describes the relationship between the velocity and force a muscle can generate with the following equation:

$$(F+a)(v+b)=(F_{\max}+a)b \tag{3.4}$$

where F is the muscle tension force; v is muscle shortening velocity; F_{max} is the maximum muscle isometric force; and a and b are constants (Winters 1990). Given that desired results of the study are the muscle forces that are required to make the model move in a specified manner, the basic Hill's model will be sufficient for the study.

It is typical to have multiple muscles activated for a single motion. This creates an over constrained condition. Given that the coupling between the head and shoulders is the focus, only the muscles that contribute to that coupling need be modeled. This leaves the trapezius, levator scapula, and the sternocleidomastoid as the major muscles under consideration. While the levator scapulae and the sternocleidomastoid are relatively large muscles, they are not significant for the motion under consideration. The levator scapulae inserts at the transverse process of the cervical vertebrae and originate at the scapula. Part of the function of the levator scapulae is yaw and roll of the head. While yaw is being studied it is not the primary motion of interest. Furthermore, only a fraction of the levator scapulae will actually contribute to yaw because of the joints being locked. Roll is ignored completely in this study. The sternocleidomastoid originates at to the sternum and the clavicle and inserts at the mastoid process. Part of the function of the sternocleidomastoid is to pitch the head forward. However, with C1-skull joint being the only active joint that allows pitch, the moment arm of the muscle becomes insignificant. For these reasons the levator scapula and the sternocleidomastoid can be neglected (Gray 2003). Additionally, only the portion of the trapezius that connects to the skull and C1 is pertinent to the analysis. The portion that inserts on the skull has origination points at the clavicle and at the scapula. The portion of the muscle that inserts at the C1 has the same origins as that portion that inserts at the skull. The muscles are mirrored across the sagittal plane, see Figure 3.8 (Yamaguchi, et al. 1990).

The anatomical connection points of the muscles are easily found with the use of published data (Gray 2003). In order to define Cartesian coordinates for these connection points, graphical representations of the bones are used. The trapezius insertion point is found to be .0793 m posterior to the occipital condyles. This insertion point allows for a representation of the HS. For an accurate representation of other species, the insertion point of the muscle will have to be measured and scaled for the model. Using Figure 3.6, a picture of a HE skull, the insertion point for HE with respect to the atlanto-occipital joint is measured. Measuring the skull and scaling the head per the Frankfurt Horizontal, the trapezius insertion point for HE was found to be .0840 m posterior to the occipital condyles (D. Bramble 2010).

In addition to the insertion and origin points, other data are needed to properly model the muscles. The pennation angle and max isometric force are needed. The pennation angle is found through published sources. The max isometric force is found by multiplying the nominal cross sectional area by 100 psi/in^2 and dividing by the number of divisions of the muscle (Yamaguchi, et al. 1990).

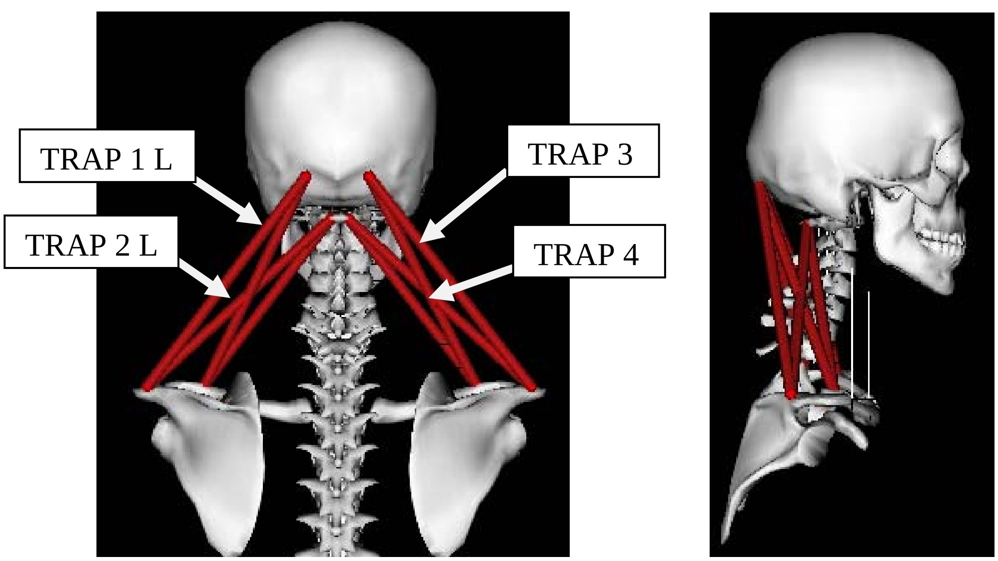

Figure 3.8: Back and side views of HS muscular attachments

In order for the model to work properly, all joints are actuated in some manner. In reality, muscles are capable of generating a moment in only one direction. Furthermore, as the trapezius is the only muscle that is modeled, other actuators are required in order to generate moments in the opposite direction. Therefore, for each active joint an ideal actuator is placed. These ideal actuators also provide additional support in the direction that the trapezius will be working, should the trapezius alone prove too weak to perform the required tasks.

3.9 Motion and GRF

In order to measure the muscle forces generated during running, the kinematics, or motion, and GRF for a complete running cycle are needed. A complete running cycle starts at heel strike and ends at the subsequent heel strike of the same foot. The data for the motion and GRF come from published sources.

Figures 3.9 – 3.14 display joint angle versus gait cycle data. All of these Figures display the data with 0% gait cycle being heel strike and 100% gait cycle being the subsequent heal strike of the same foot. Vertical lines in the graphs show toe off. Figures 3.9 – 3.11 display kinematic data for the lower body and are adapted from Novacheck (1998). Figure 3.12 provides the kinematic data for the trunk and is adapted from Schache, Blanch, et al. (2002). Figures 3.13 and 3.14 provide the kinematic data for the shoulder and elbow, respectively, and are adapted from Hinrich (1990). The data for the lower body are useful as a sanity check to make sure that the entire motion of the model is reasonable. As the origin of the model is set at the pelvis, motion for the subsequent segments are needed to position and orient the head appropriately.

Figure 3.15 displays the GRF data for a HS running 4.5 m/s, and is adapted from Cavanagh and Laforune (1980). As the curve does not give a definite point of toe off, the time of 214 ms was determined as an average stance time for a HS running at the specified speed (Munro, Miller and Fuglevand 1987).

The available kinematic data provided the joint motions for most of the joints in the body. The data do not provide translational data for the pelvis, neck motions, or shoulder rhythm data. The lacking data are derived from the available data. As the study is focused on the head and neck movements, the pelvis translational data required are the vertical data. The horizontal data can be ignored because that motion is secondary. For this reason the horizontal, roll, joints in the neck are locked. The vertical data during the stance phase are derived using the leg lengths and angles and some simple geometry. The rest of the vertical translational data is derived with a vertical projectile equation. Using the time between toe off and heel strike, the vertical height of the pelvis at toe off is the start point for the projectile equation. The final point is the vertical height of the pelvis at heel strike. The neck motions are assumed to be the motion required to counteract the combined motions of the pelvis and trunk. The shoulder rhythm is derived by applying the linear regression equations developed by Groot and Brand (2001) to the shoulder angles.

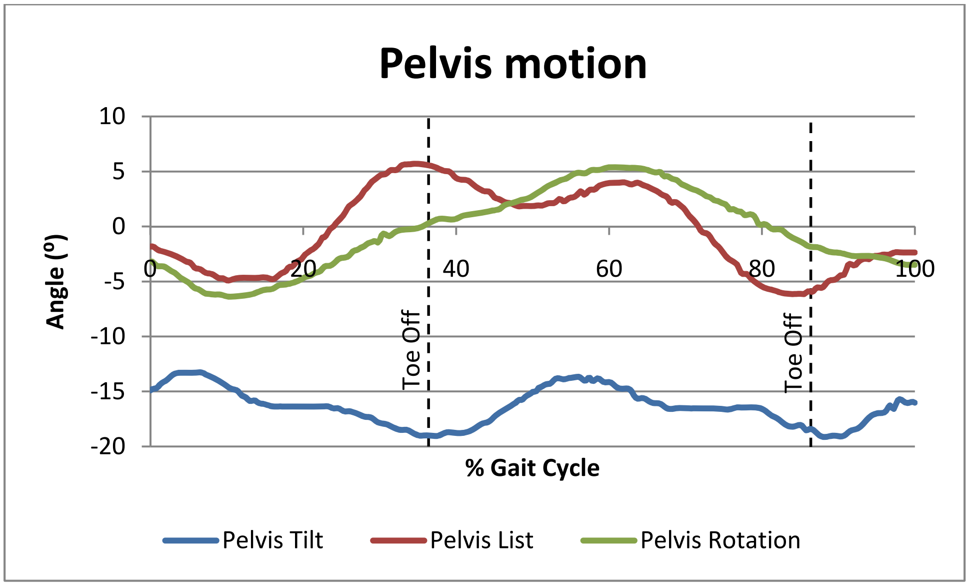

Figure 3.9: Pelvis list, rotation, and tilt adapted from Novacheck (1998)

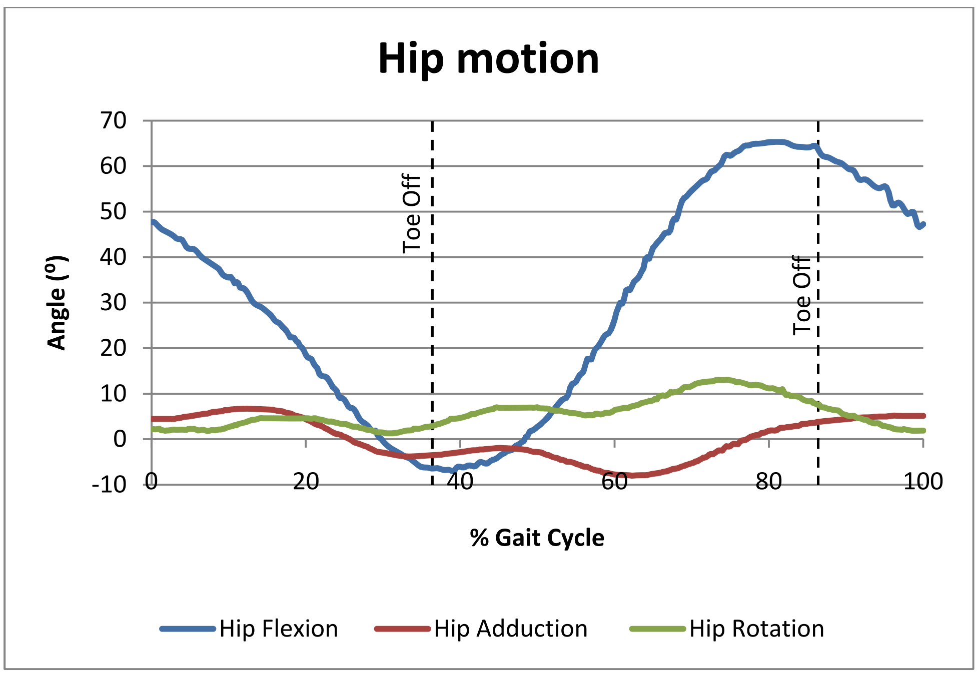

Figure 3.10: Hip ad-abduction and flexion/extension adapted from Novacheck (1998)

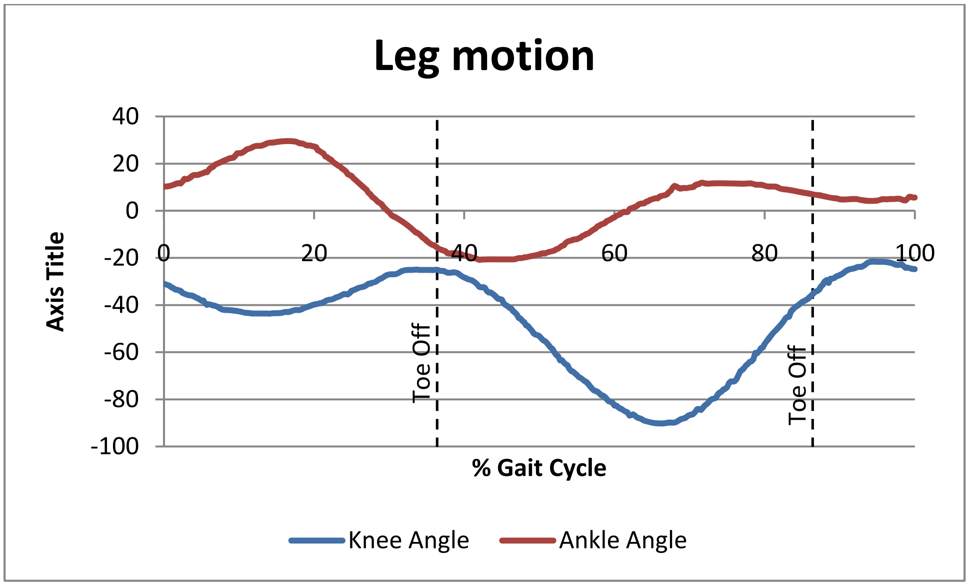

Figure 3.11: Knee flexion/extension and ankle, or dorsi/plantar flexion adapted from Novacheck (1998)

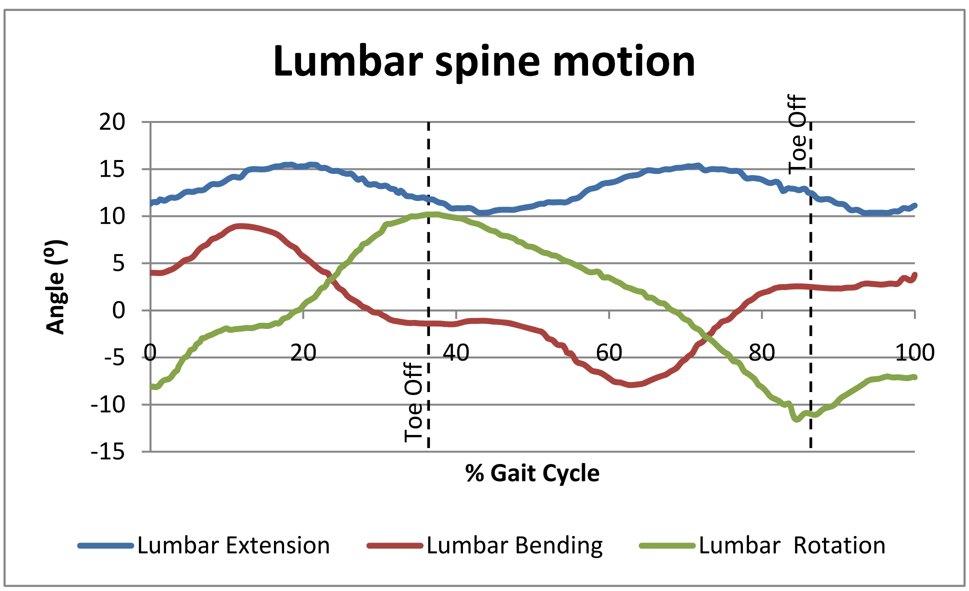

Figure 3.12: Lumbar spine flexion/extension, lateral bend, and rotation adapted from Schache, Blanch, et al. (2002)

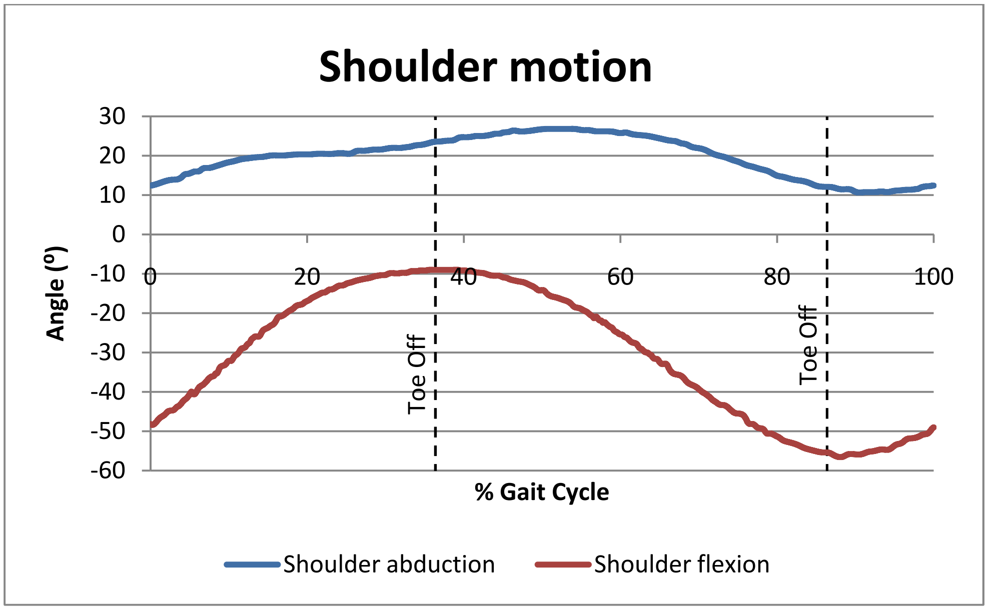

Figure 3.13: Shoulder abduction and flexion adapted from Hinrich (1990)

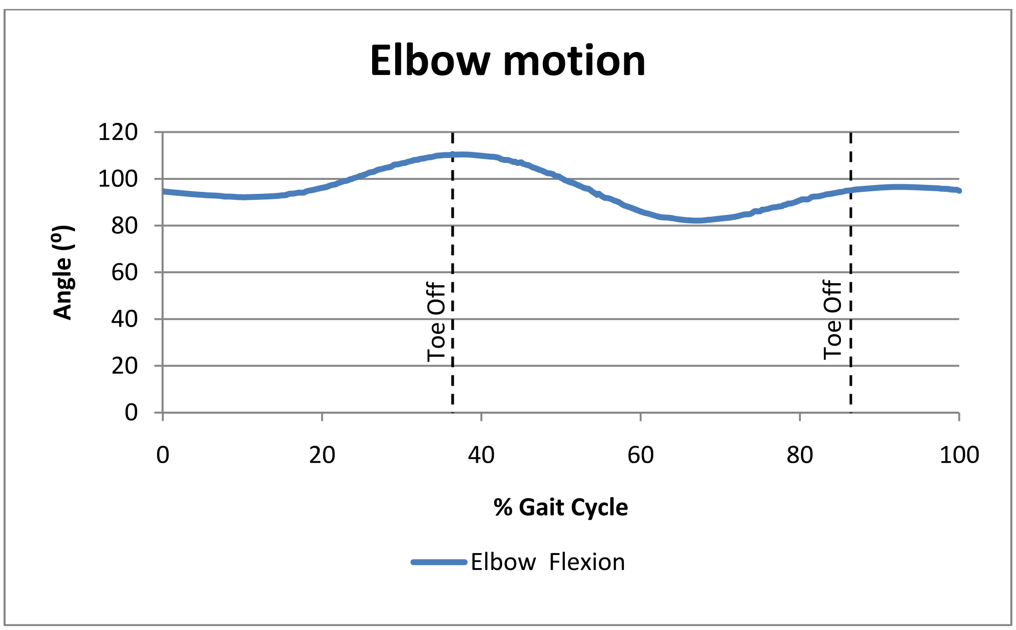

Figure 3.14: Elbow data adapted from Hinrich (1990)

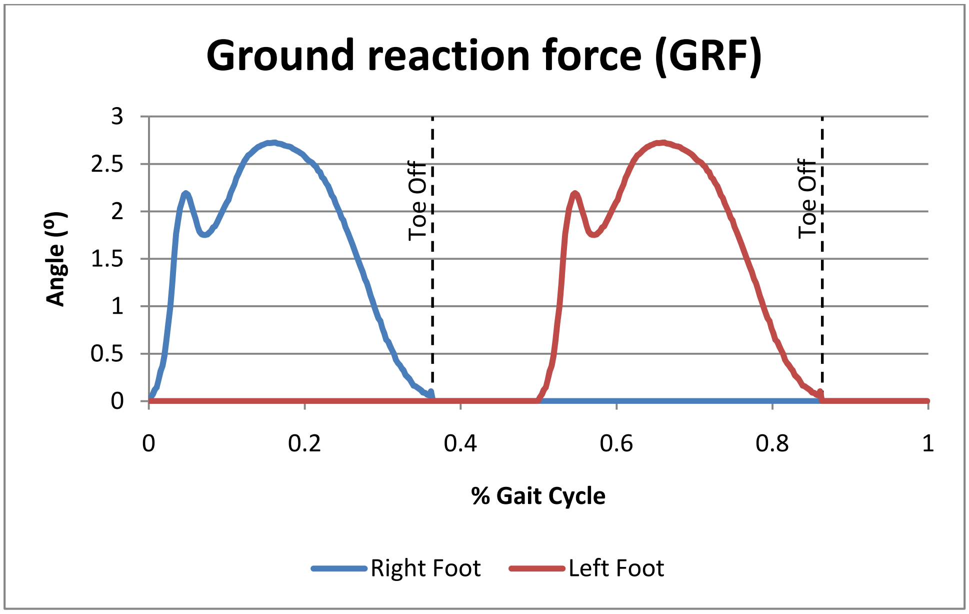

Figure 3.15: General GRF curve for running in B.W. adapted from Cavanagh and Lafortune (1980)

3.10 OpenSim

As a means to calculate the muscle forces for the running motion, the open source software OpenSim is used. This program, developed by Delp, et al. (2007), allows for the creation and analysis of a musculoskeletal skeletal system. The creation of the model segments in OpenSim can be done using simple chain-link dynamics. If desired, OpenSim allows for more complicated joints to be used. One of the benefits of OpenSim is that it allows for geometry files to be attached to the body segments. These geometry files can be 3D scans of real bones. This allows for a realistic graphical model. Such a model is helpful in the placement of the muscle insertion and origin points.

To analyze the muscle forces for the prescribed motion, OpenSim can perform a static optimization. Static optimization resolves the joint moments into individual muscle forces at each instant in time. If the joint has ideal actuators the following equation is used:

$$\sum_{m=1}^{nm} \left(a_m F_m^0\right) r_{m,j} = \tau_j \tag{3.5}$$

If the joint is constrained by force-length-velocity properties, the following equation is used:

$$\sum_{m=1}^{nm} \left[a_m f\left[F_m^0, l_m, v_m\right]\right] r_{m,j} = \tau_j \tag{3.6}$$

The minimizing objective function is as follows:

$$J = \sum_{m=1}^{nm} \left(a_m\right)^p \tag{3.7}$$

where nm in the number of muscles in the model; a_m is the activation level of muscle m at a discrete time step; F_m^0 is a muscle's maximum isometric force; l_m is the muscle's length; v_m is a muscle's shortening velocity; $f\,[F_m^0, l_m, v_m]$ is a muscle's force-length-velocity surface; $r_{m,j}$ is a muscle's moment arm about the j^{th} joint axis; τ_j is the generalized force acting about the j^{th} joint axis; and p is a user defined constant.

To generate the models for this study, parts of established models are used as a frame work. The body segments and joints for the lower body and torso come from a model Delp, Loan, et al. (1990) developed. The body segments and joints for the right shoulder and arm are adapted from a model Holzbaur, Muray and Delp (2005) developed. The right shoulder and arm are mirrored to create the segments and joints for the left shoulder and arm. The neck and head portions are adapted from model created by Vasavada, Li and Delp (1998). Added upon this frame work are the anatomical inputs and assumptions necessary for this study. Six models are created for this study. The models created are as follows. See Table 3.4:

- (HS) 50th percentile HS; the geometry and actuator represent a 50th percentile HS
- (HS stiff) HS with locked shoulders and arms; the 50th percentile HS is modeled with all shoulder and arm joints locked in a neutral position
- (HE COM) HE with the uncorrected COM; the HS model is modified to have a head COM representative of a HE
- (HE COM corrected) HE with the corrected COM; the head COM is corrected to account for the relationship of the ear to the atlanto-occipital joint
- (HE COM and muscles corrected) HE with the corrected COM and muscle insertion points; the HE model is corrected to account for the anatomical differences in the skull
- (gorilla COM) gorilla with the uncorrected COM; the HS model is modified to have the head COM representative of a gorilla.

Table 3.4: Model setup summary

	COM (m)		Skull insertion (m)	
	horizontal	vertical	horizontal	vertical
HS	0.0228	0.0533	0.0793	0.0237
HS stiff	0.0228	0.0533	0.0793	0.0237
HE	0.0298	0.0398	0.0793	0.0237
HE COM corrected	0.0414	0.0281	0.0793	0.0237
HE COM & muscles corrected	0.0414	0.0281	0.0840	0.023
gorilla COM	0.0549	0.0041	0.0793	0.0237

CHAPTER 4

RESULTS

4.1 Introduction

When OpenSim runs, the results produced from the static optimization are the muscle and joint forces needed to move the model according to the prescribed motion while matching the applied external forces. For the analysis in question, the muscle forces produced are for the portion of the trapezius that connect to the skull and C1. Table 4.1 describes the insertion and origin points for the trapezius portions used.

4.2 Results

The results are shown in Figures 4.1 – 4.6. The vertical dashed lines signify toe off.

Table 4.1: Connection points of the trapezius portions

Name	Origin	Insertion
TRAP 1	Scapula R	Skull
TRAP 2	Scapula R	C1
TRAP 3	Clavicle R	Skull
TRAP 4	Clavicle R	C1
TRAP 1 L	Scapula L	Skull
TRAP 2 L	Scapula L	C1
TRAP 3 L	Clavicle L	Skull
TRAP 4 L	Clavicle L	C1

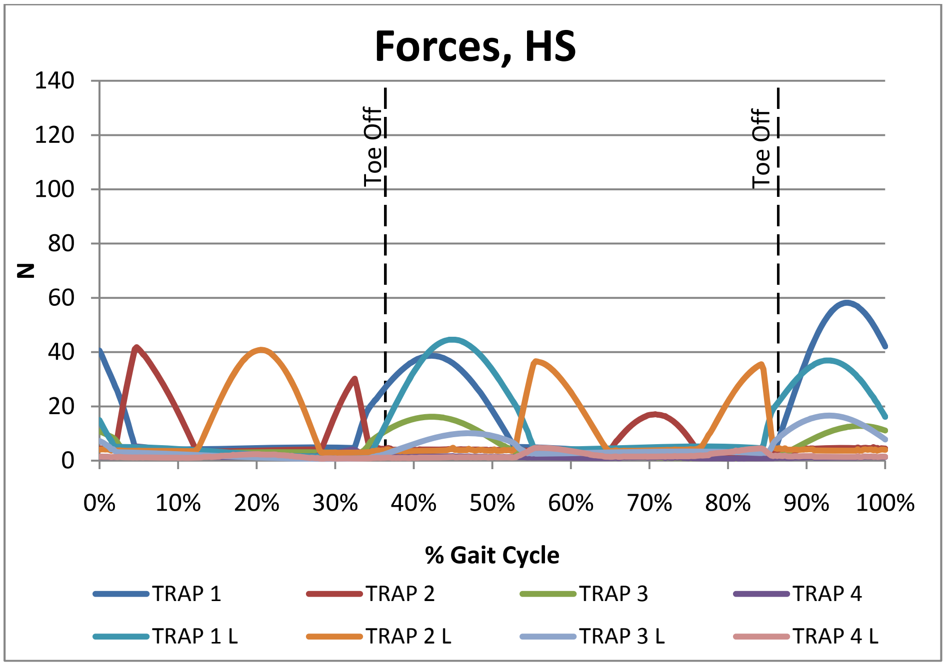

Figure 4.1: Forces, HS

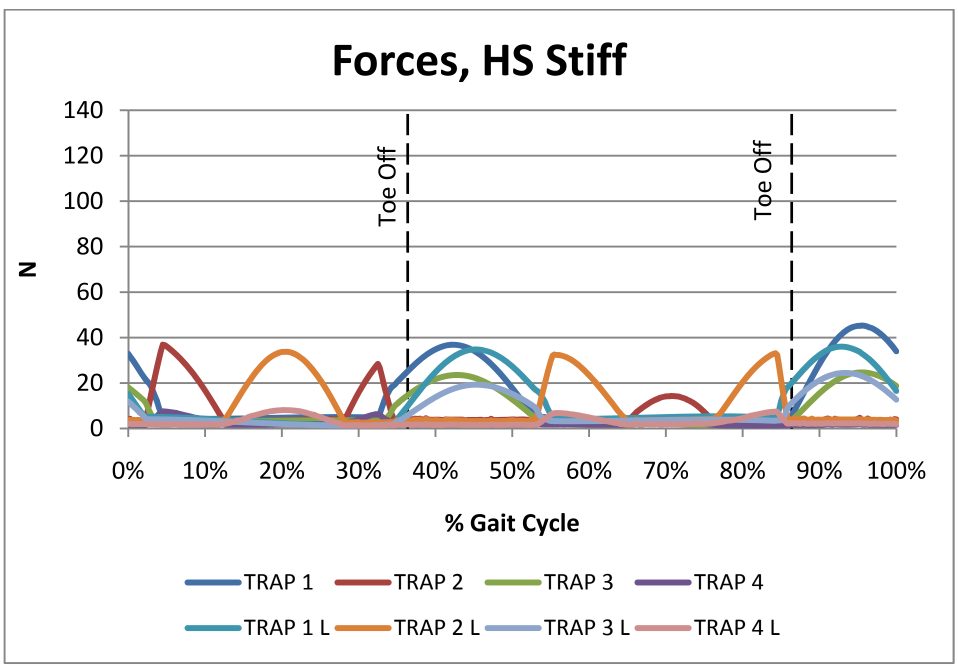

Figure 4.2: Forces, HS stiff

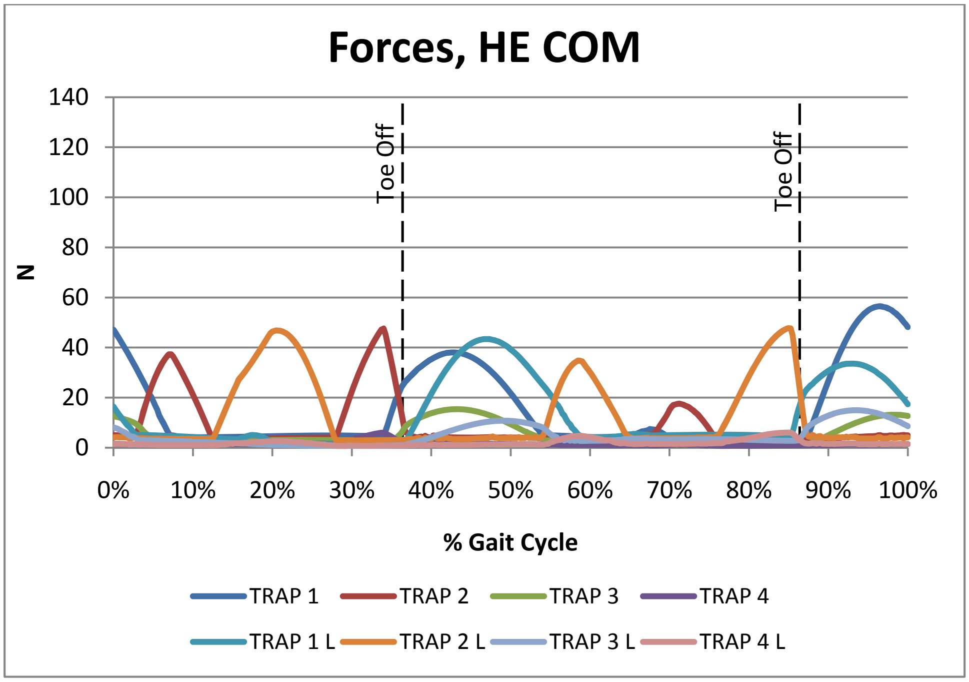

Figure 4.3: Forces, HE COM

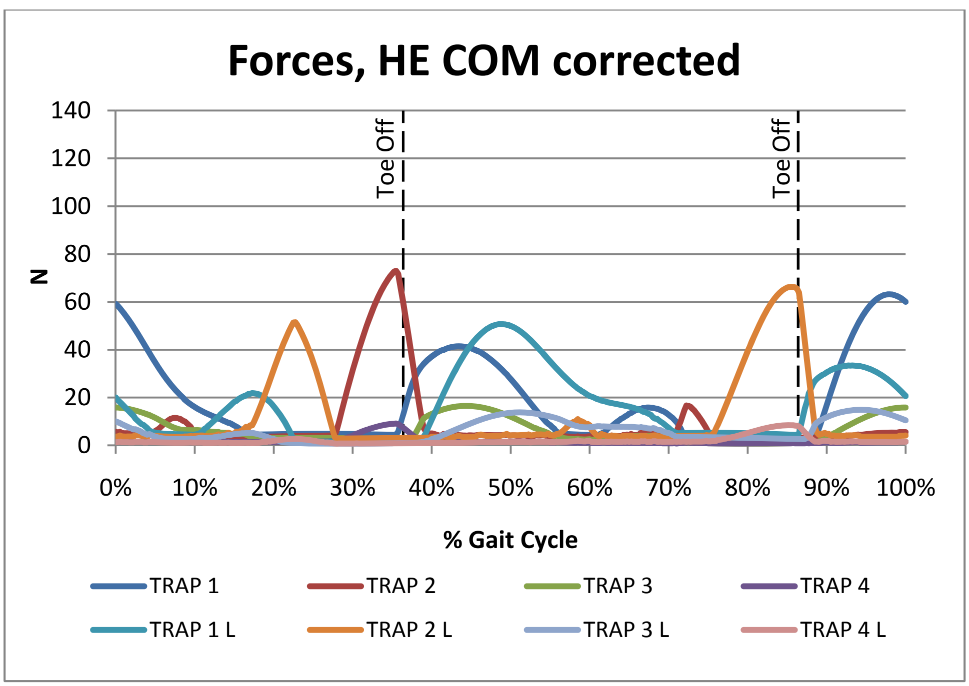

Figure 4.4: Forces, HE COM corrected

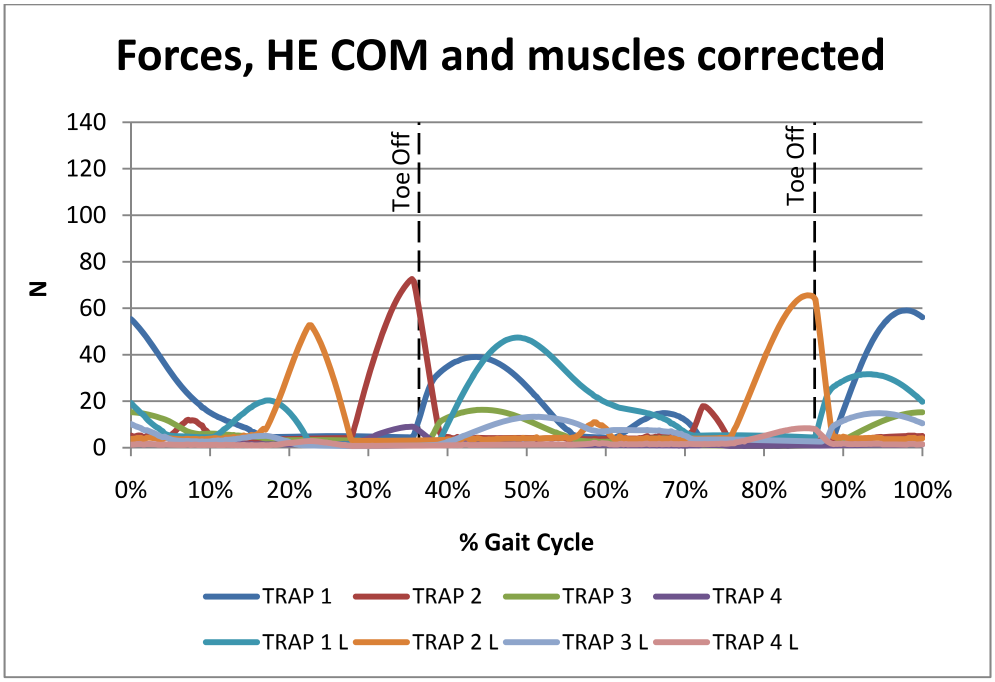

Figure 4.5: Forces, HE COM and muscles corrected

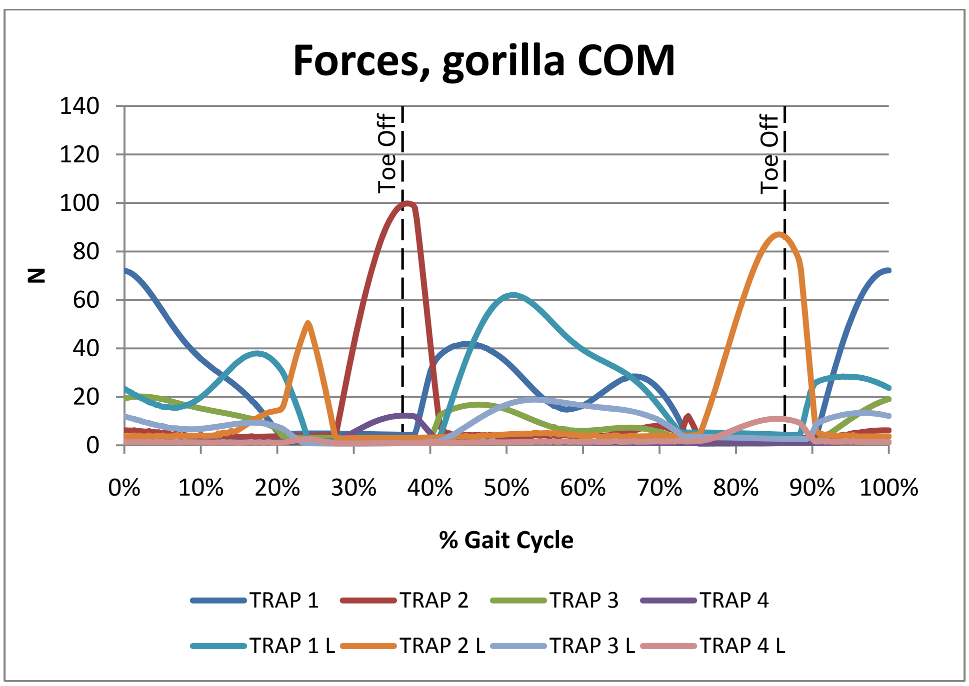

Figure 4.6: Forces, gorilla COM

CHAPTER 5

DISCUSSION

5.1 Introduction

In order to better facilitate the analysis of the data, several steps have been taken to present the data in a more concise fashion. To postprocess the data, the following steps are taken:

1. Sum the forces for all muscle elements at each time increment and integrate over the gait cycle
2. Find the power for each muscle element at each time increment
3. Sum the power of all muscle elements at each time increment and integrate over the gait cycle
4. Sum the absolute value of the moment arms about the axes for Pitch and Yaw for each muscle element at each time increment
5. Calculate the sum of the absolute value of the moments about each of the two axes for each muscle element at each time increment
6. Integrate the moments over the gait cycle
7. Find the vector sum of the moments about the axes
8. Plot and compare.

In order to calculate the power for each muscle element, the following equation is used:

$$P = (v_i - v_o) * f \tag{5.1}$$

where P is the power; v_i is the velocity of the insertion point; v_{oi} is the velocity of the origin point; and f is the force of a muscle element.

The moment arm at each time increment is found with the following equation:

$$r = \left(A \cdot \left(R \times \frac{F}{|F|} \right) \right) \tag{5.2}$$

where r is the moment arm; A is line representing the axis equal to a unit value; R is the line between the joint origin and the insertion point of the muscle element; F is the line between the insertion and origin points of the muscle element. To find the moment, the moment arm is simply multiplied by the applied force of the muscle element. To integrate the different values, a simple trapezoidal integration is performed.

Summing the forces, powers, and moments for each time step allows for a single number to summarize all the actions in that instance of time. Summing the moments together also allows for the residual moments to be included in the comparison. The residual moments provide the motion to the model that the trapezius cannot. A comparison of the moments is useful to determine which aspect of the motion is more critical than the other. As the purpose of the study is to compare the efficiency of running for different species, it is desirable to compare the power used. As the moments are a directional quantity, the absolute value is taken to provide a means of determining how that energy is used. Integrating the different values allows a single number to be used to compare the different cases.

Following the postprocessing steps, Figures 5.1 – 5.6 show the summed trapezius forces. Figures 5.7 - 5.12 show the power used by the trapezius. The vertical dashed lines signify toe off.

5.2 Results summary

To summarize the data in a single form, the integrated values of the forces, power, moment arms, and moment are presented in Table 5.1.

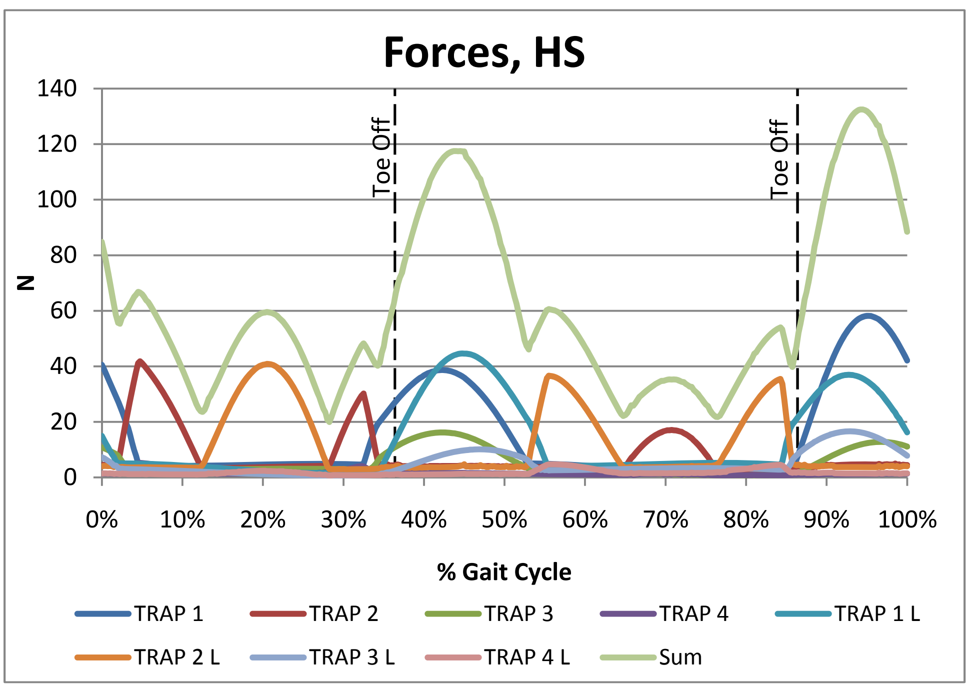

Figure 5.1: Forces, HS

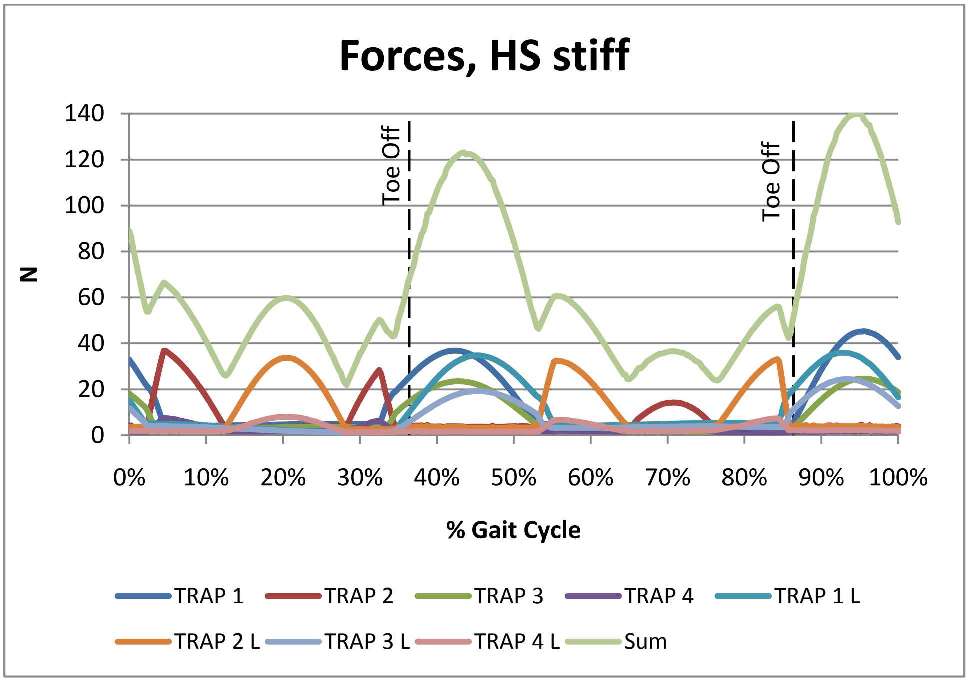

Figure 5.2: Forces, HS stiff

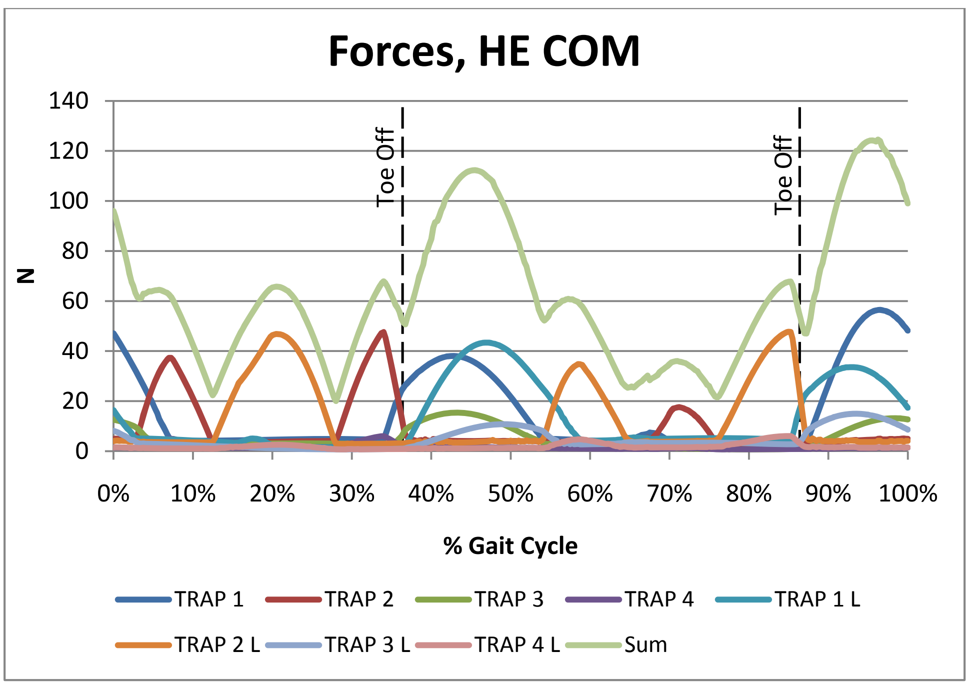

Figure 5.3: Forces, HE COM

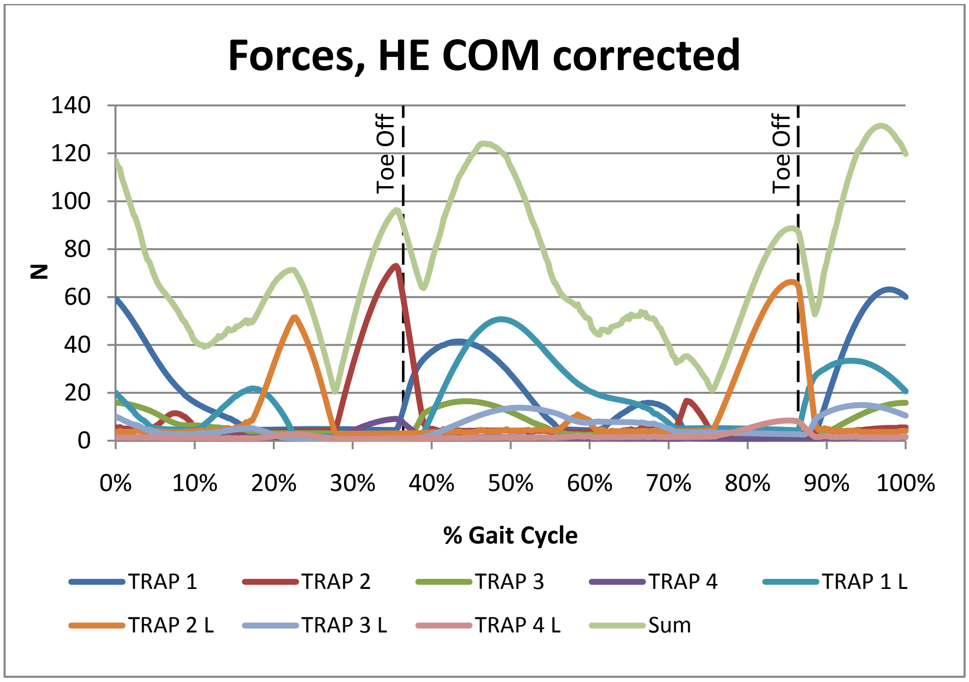

Figure 5.4: Forces, HE COM corrected

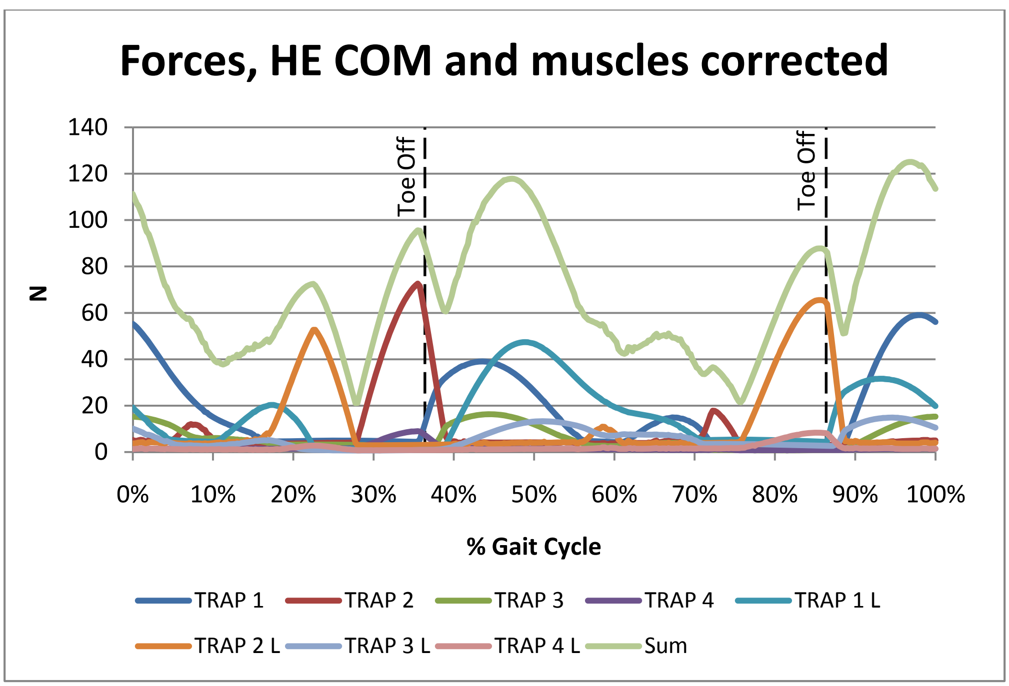

Figure 5.5: Forces, HE COM and muscles corrected

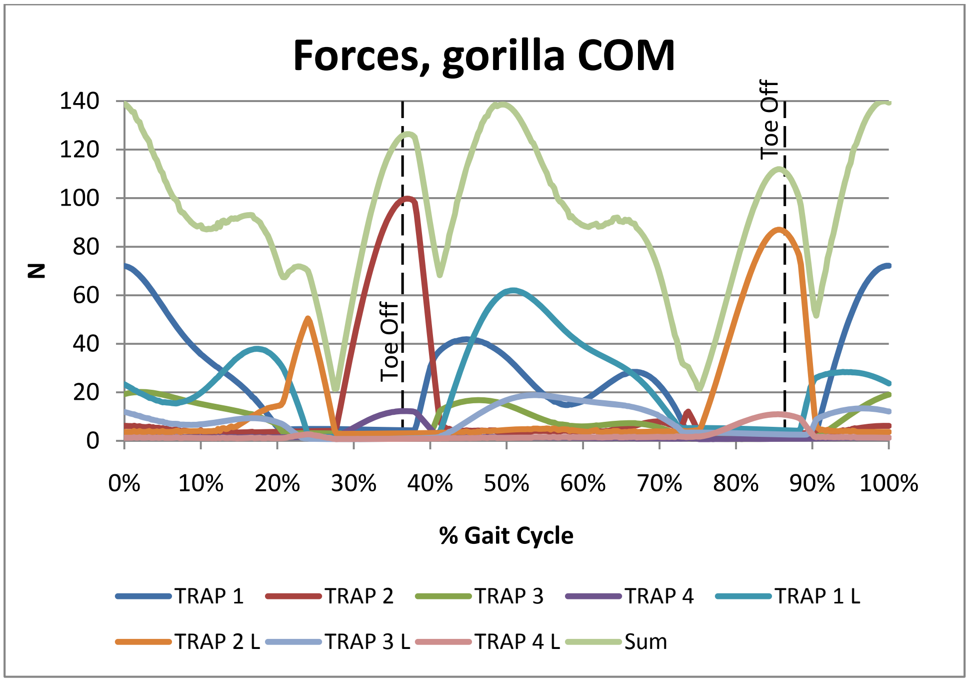

Figure 5.6: Forces, gorilla COM

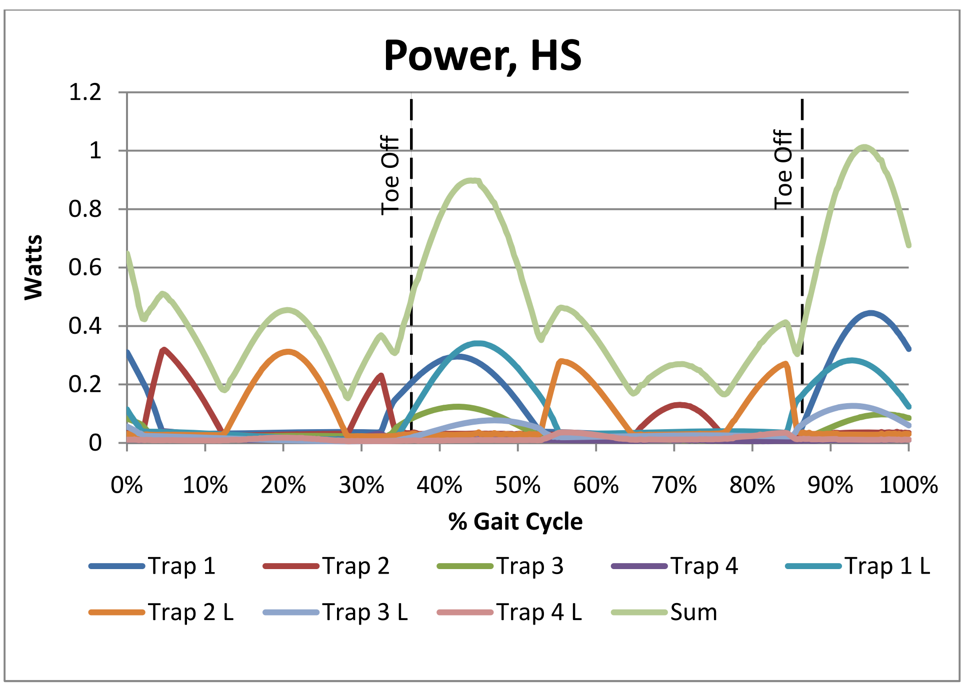

Figure 5.7: Power, HS

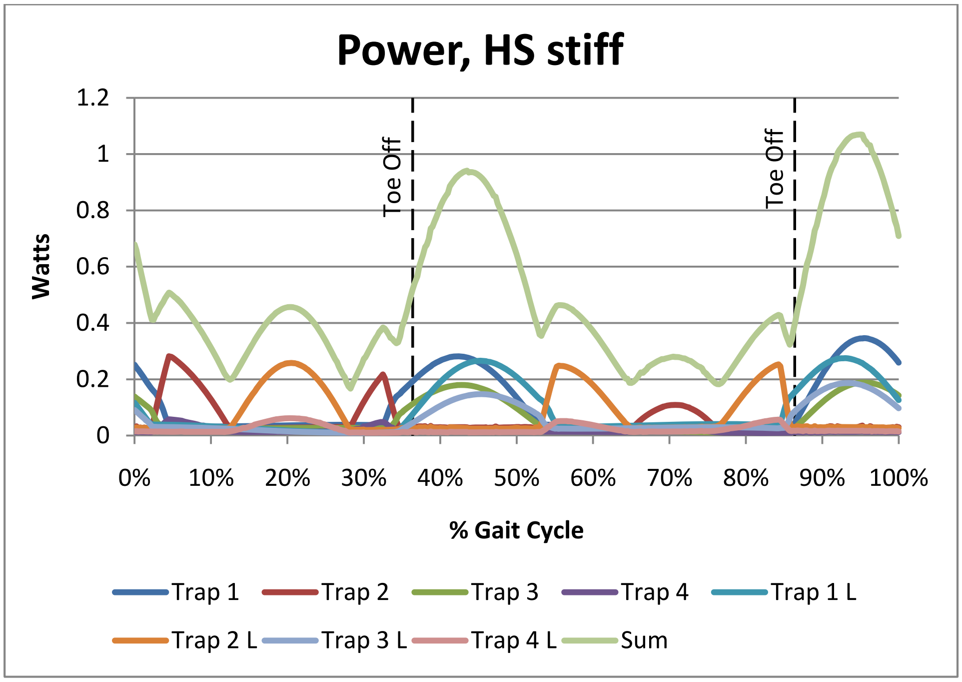

Figure 5.8: Power, HS stiff

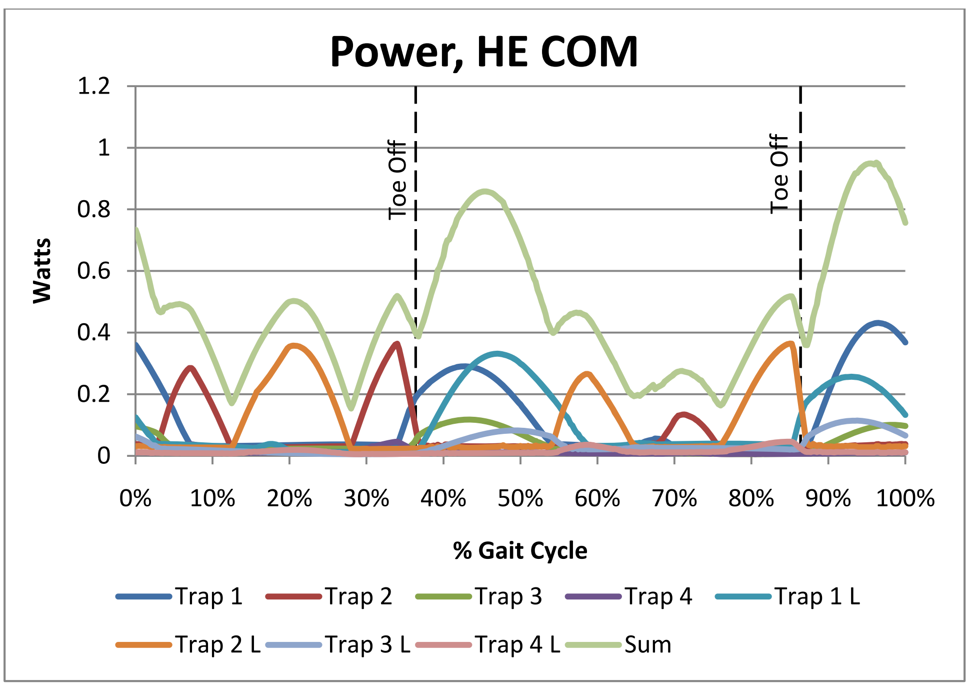

Figure 5.9: Power, HE COM

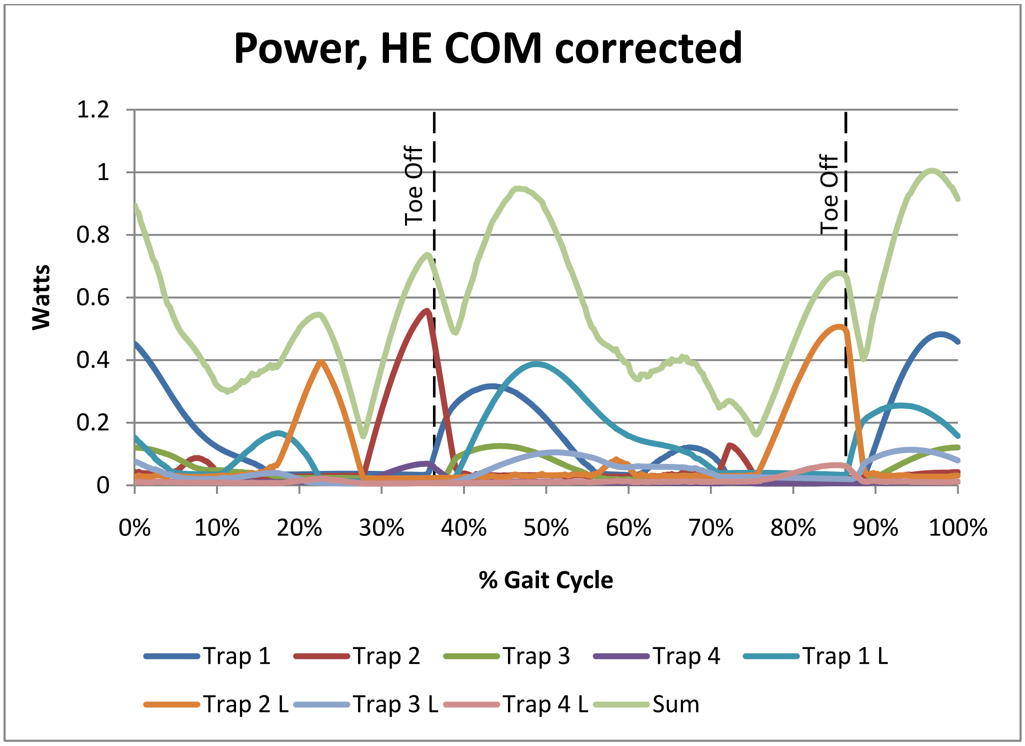

Figure 5.10: Power, HE COM corrected

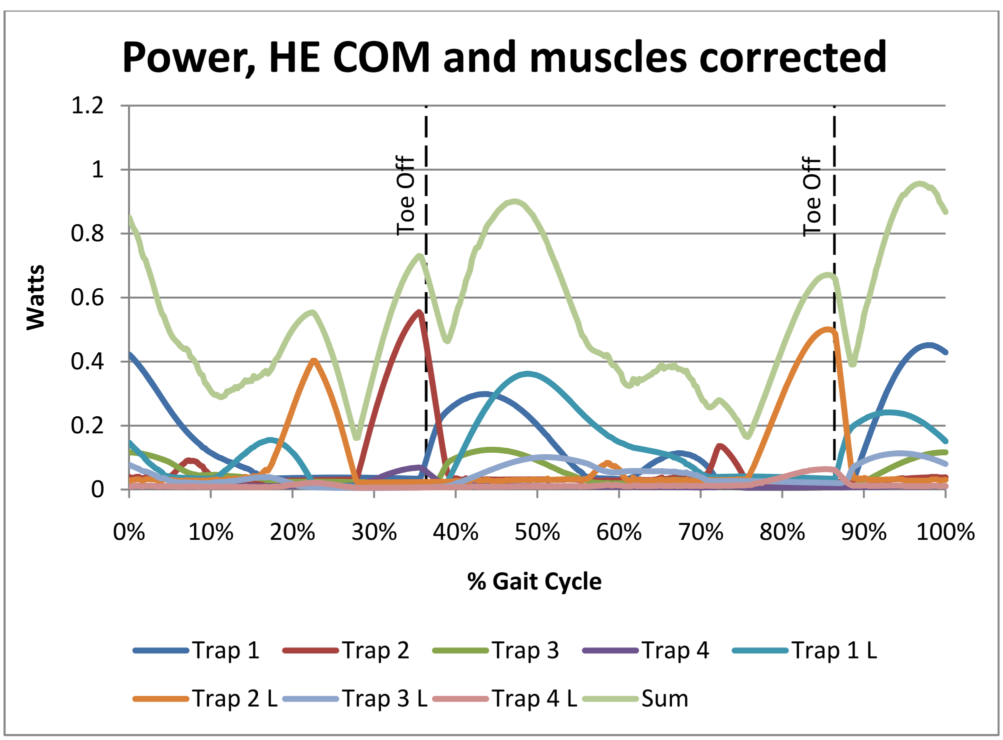

Figure 5.11: Power, HE COM and muscles corrected

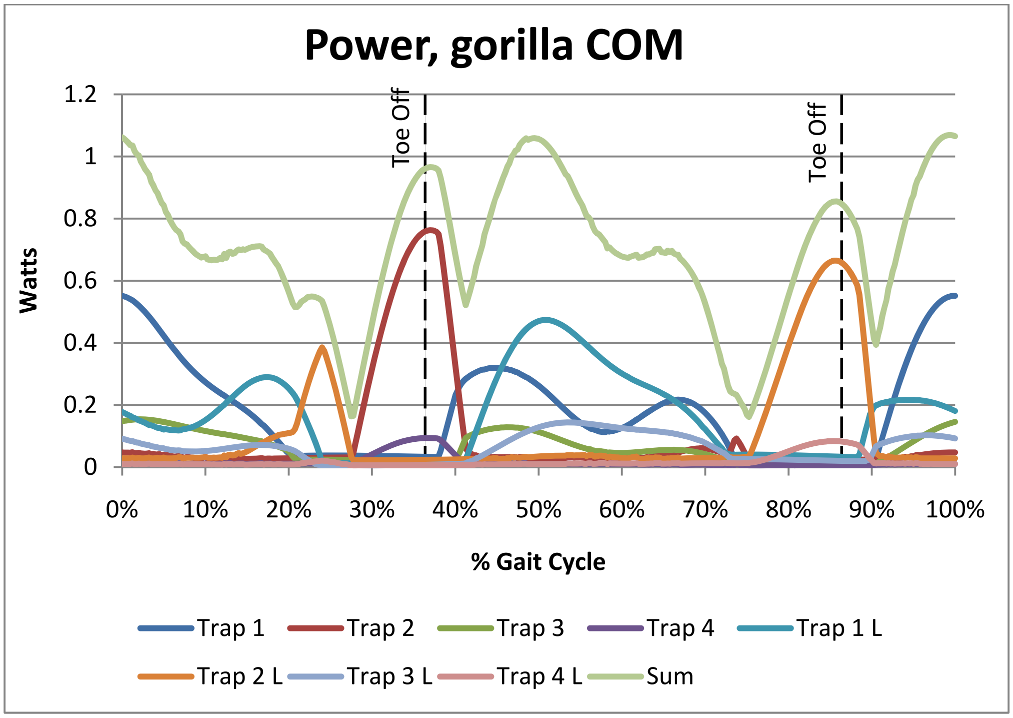

Figure 5.12: Power, gorilla COM

Table 5.1: Results summary

	Impulse (N*s)	Energy (J)	Sum of Average Moment Arm	Rotational Impulse (Nm*s)				
				Yaw 2	Pitch 1	Vector Sum	Residual Vector Sum	Total Vector Sum
HS	35.685	0.273	0.417	1.272	1.603	2.059	0.599	2.658
HS stiff	37.141	0.284	0.420	1.415	1.641	2.175	0.610	2.785
HE COM	36.645	0.280	0.417	1.289	1.615	2.080	0.393	2.473
HE COM corrected	41.898	0.320	0.417	1.518	1.934	2.475	0.408	2.882
HE COM and muscles corrected	40.545	0.310	0.435	1.545	1.940	2.495	0.411	2.906
gorilla COM	54.018	0.413	0.417	1.959	2.507	3.201	0.556	3.757

5.3 General errors

As this study relies on measured values as a source for inputs into a mathematical model, there are undoubtedly sources of errors at every level. Each anatomical measurement is subject to some sort of error due to the limitations of the measuring device. Along with the simple measurements of mass and length, determination of COM and the inertial parameters are also subject to errors. These inertial parameters are dependent upon how well the body parts are segmented. Body segmentation can become critical with joints such as the hip and joint and simplifications of the spine. These derived measurements are also static approximations of moveable factors. The human body is not a rigid structure; there is constant movement of all parts. The real COM and inertial parameters will vary with the state of the muscles, orientation of bones, blood flow, respiration, etc.

The creation of a model to represent the body is often based upon chain-link dynamics. This method of modeling can have inherent errors in the representation of the body joints. Each segment is an element unto itself. This means that body segments, such as the pelvis and thigh, will have representational errors if they share components. For simplicity, the joint are represented as simple rotational joints about a stationary axis. This makes the assumptions that the joint has no translational aspects and that the axis remains in one spot and in one orientation. Furthermore, in order to represent joints with multiple degrees of freedom, the joints must be ordered. This ordering can cause numerical errors and singularities where the joint will lose a degree of freedom in certain situations. Furthermore, these joints must be measured correctly and be placed in the proper orientation and position to allow proper rotation.

Modeling muscles also has inherent limitations. Current techniques allow muscles to be modeled as strings with various properties. These techniques do not consider the volumetric or mass properties of the muscles. The lack of consideration for mass and volumetric properties of the muscles will affect the direction of pull of the muscles and the center of mass of the body segment. Coupled with the representation of being strings is the placement of the insertion and origin points. Most anatomy texts will describe boney landmarks to which a muscle is attached. However, x, y, z coordinates are required for mathematical modeling. There are texts that do give Cartesian coordinates for muscle attachment points. However, these measurements are typically from specific cadavers. One is then set with the difficulty of scaling the specific measurements to the desired model (Yamaguchi, et al. 1990). Attaching a 3D graphical representation of real bones to a visual representation of the model in question is possible. The errors in such a case will stem from the accuracy of the 3D scan of the bone, the placement graphical origin and orientation of its coordinate system. With a 3D graphical representation of the bone, an attachment point, not an area, will still need to be identified. Muscles attach to areas, not points. Therefore, an attachment will be simplified to a single point, or a series of points.

There are errors in the representation of the functional aspects of muscles. To properly represent the functional aspects of a muscle there must be a mathematical model. The current mathematical models for muscles have errors (Winters 1990). Furthermore, these mathematical models are dependent upon properly measured parameters of muscles. These properties provide information about how the muscle will perform (Yamaguchi, et al. 1990). Due to the limitations of all measurement devices, there are errors associated with all measured values.

In addition to the errors associated with representing the anatomy of a biological entity, there are errors with the description of movement. A widely used technique to measure body movement is 3D video measurements. Much of the accuracy of these measurements is based upon the skill of a trained technician to place reflective markers on the skin covering a bony landmark. The placement of these markers is driven by how the skin moves over the bones. If the skin moves a significant amount over the bones as the subject is in motion, then the measurement will be inaccurate. Other errors with this system include the ability of the cameras to pick up the reflections of the markers, the size of the markers, and accuracy to which the system was calibrated (Cappozzo, et al. 1995).

Measurement of GRF has its own errors. Some of these errors come from the accuracy of the equipment. In addition to the actual equipment, initial contact and toe off also need to be appropriately identified. These points are identified by the force measured by sensor to be with some limits. If the limits are wrong, then incorrect GRF could be recorded. The forces also need to be attached to the appropriate location in the body. The GRF can be different if the initial contact of the foot with the ground occurs at different points on the foot (Cavanagh and Lafortune 1980)

Besides the errors associated with the representation of a biological system in motion, there are also errors stemming from the mathematical techniques used to analyze the system. The data used as inputs are often from different sources. Thus, the data must be correlated and scaled properly. The GRF must be of the appropriate magnitude for the running speed and mass of the subject. The motion must align with heel strike and toe off.

To properly represent the biological system, the model will have multiple actuators acting in the same direction to achieve the same movement. This means that the system, mathematically, is over constrained. Therefore, optimization techniques must be used to determine the optimal force each muscle exerts. These mathematical methods distribute a total force amongst an array of subcomponents. This is done by attempting to minimize the errors each subcomponent will have.

5.4 Study specific errors

While there are many sources of error in every aspect of this study, there appear to be some specific errors associated to this study. The general setup of the study is for models to be created and inputs applied. These models and inputs are assumed to be symmetric about the sagittal plane. Based on this assumption, the forces on each side of the body should be of the same magnitude but with a phase difference of 180 degrees. However, the results do not reflect this logical outcome of the assumption. What occurs is that the forces associated with the different sides of the body are not symmetrical.

Given the nature of the analysis, the primary causes for errors are faulty modeling and inputs. Should the models and inputs be correct, then the assumption used to create those models and inputs is faulty. The model was created by inputting published values for a body segment and then mirroring those values about the sagittal plane. The inputs were created in a similar fashion. The difference with the inputs is that right and left side are out of phase by 180 degrees. The discrepancy in the results could have come about if these values were not mirrored properly.

However, in reality, the body is not perfectly symmetric about the sagittal plane. Typically a person has a dominant side that is stronger than the other. However, this asymmetry is apparent only if individual measurements of the left and right sides of test subjects are taken. Furthermore, the pelvis, torso, and head are not absolutely symmetrical about the sagittal plane. This discrepancy will not be apparent with the model, the kinematic inputs will show it. Although, the kinematic inputs for the model of the limbs are mirror images of themselves, the data for the pelvis, torso and head are singular.

A simple way of determining if the kinematic inputs for the pelvis, torso and head are symmetrical is to find the average angle of the motion data. The average angle for the head is not necessary because that motion is derived from the pelvis and torso. Figure 5.13 shows the pelvis and trunk motion data as inputted in the model. Table 5.2 summarizes the motion data. The rotational data for the pelvis and trunk are not symmetrical. Thus, the results of the analyses will not be symmetrical.

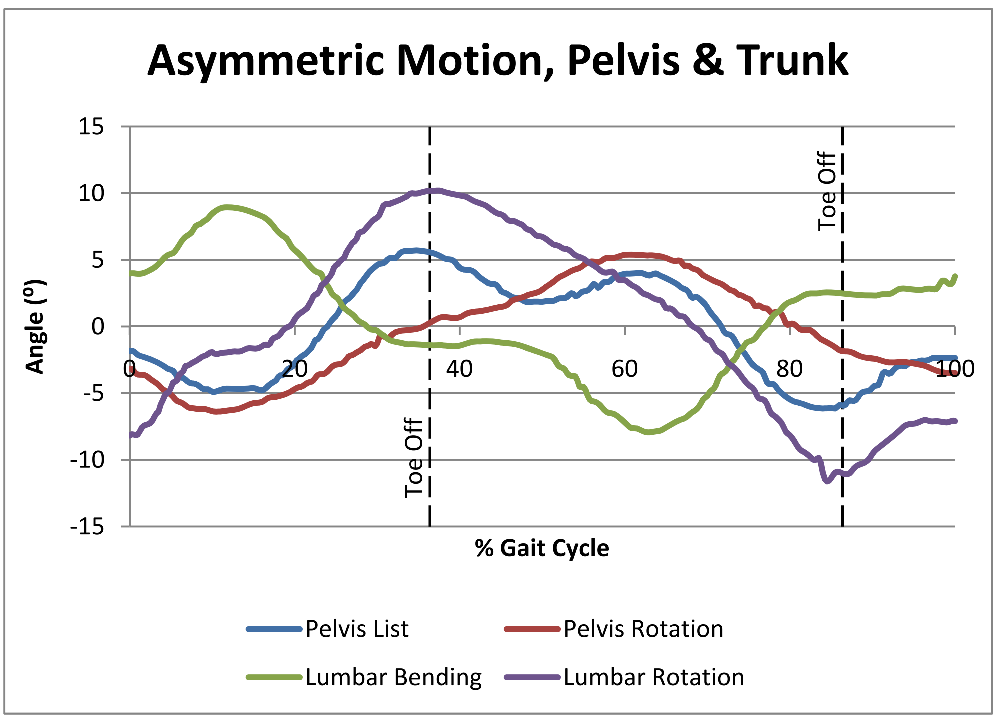

Figure 5.13: Pelvis and trunk motion as inputted in the analyses

Table 5.2: Summary of pelvis and trunk motion.

	Pelvis list	Pelvis rotation	Lumbar bending	Lumbar Rotation
Average angle (°)	-0.36	-0.49	0.57	0.03
Max angle (°)	6.14	6.38	8.95	11.62
% offset of max	5.9%	7.7%	6.4%	0.2%

5.5 Observations

The results of the analyses show that HS uses the least amount of energy, over all, to keep the head stable during a running cycle. The HE, HE COM corrected, and the gorilla COM cases have the same muscle insertion points as the HS. However, the three cases all require more energy from the trapezius. The HE COM corrected and the gorilla COM cases also require larger rotational impulses to keep the head stabilized. This means that the closer the COM is to the joint origin, the easier it is to keep the head stabilized.

To continue the study of endurance running, the comparison between moving and not moving the shoulder while running is performed. Having the shoulders stiff, over all, creates larger moment arms than if the shoulders were moving. However, the linear and rotation impulse and the energy required to keep the head stable were greater with the stiff shoulders. This means that the movement of the shoulders helps to stabilize the head.

There are a couple of possible explanations for this behavior. In general, having the connection between the shoulders and the head should be beneficial to head movement. This is because of the increased moment arm that such a connection provides. The increased moment arm would allow an array of muscles to use less force to move the head. Connecting the head to the shoulders with an active system will allow for an increase to the head’s inertia at beneficial times. These beneficial times are when it is desirable to keep the head stationary. Furthermore, the motion of the shoulders can be used to decrease the required muscle force. If a platform is pulling an object and being pulled in the same direction that the object is being pulled, then the force applied to the object is the sum of the two pulling forces. Therefore, if the right shoulder is shifting in a posterior direction at the same time the head it rotating to the right, the shoulder muscles can work less than if the shoulder was stationary.

When analyzing different species, the HE and HE COM corrected show the difference of not taking into account the placement of the COM with respect to the occipital condyles. When the COM for HE is placed with respect to the ear of the HS, the results show that the HE has slightly higher muscle impulses and energies. However, the overall rotational impulses required for the HE are less. This implies that the other muscles in the HE’s neck are working less than those of the HS. Thus, the HE could be more effective at head stabilization than HS. However, when the COM of HE is compensated for the placement of the occipital condyles of its species, the results show that the HS has both lower energy and impulses.

Part of coupling the shoulders to the head is the placement, insertion and origin points, of the muscles. The HE COM and muscles case shows the effects of moving the trapezius muscle farther back on the head. The results show that the muscle impulses and energy used in HE COM and Muscles corrected are less than HE COM corrected. This corresponds to the increase of the moment arm from HE COM corrected to HE COM and muscles corrected. However, the overall rotational impulse of HE COM corrected is less than HE COM and muscles corrected. A possible explanation of this is that the minimum force of a muscle is never zero. A muscle always exerts some finite amount of tension. By increasing the moment arm of the muscle, the active force of the muscle will increase the applied moment on a joint. However, the increase in the moment arm will also increase the applied moment on the joint of that passive muscular force. Thus a larger moment opposing that generated by the moved muscle is needed. The benefits of increasing a muscle's moment arm for an improved application of the active force must outweigh the drawbacks incurred by the muscle's passive force.

CHAPTER 6

CONCLUSION

6.1 Conclusion

Through the analysis of representative mechanical models, the forces need to stabilize the head during the bipedal running of HS are determined. Despite the errors associated with each aspect of the study, the analysis shows that the anatomical features of HS enable them to be more efficient at stabilizing the head than their ancestors. The effort a *Homo sapiens* needs to keep its head stable during running is less than that of its ancestors. This reduction of effort is achieved by moving the COM of the head closer to the occipital-atlanto joint and coupling the head to moving shoulders with muscles.

6.2 Future Work

There are many directions in which this study can be taken. This study has a relatively small focus with only a portion of the trapezius, and very few neck muscles, being modeled. It would be good to expand the model with more muscles and more degrees of freedom in the neck. Specific inputs for the kinematics of the head would also be helpful. These improvements would allow for definitive quantities of energy needed to stabilize the head. Another direction for the study would be to increase the level of detail in the model and inputs, but for only very small time segments. These narrow studies would be used to determine the effects of each detail on the efficiency of running. Yet another direction for the study would be for optimization purposes. Each parameter in the model could be tweaked to determine how optimal HS are at running.

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